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About Authors

• A. H. R. Fedden *began his automotive engineering career back in 1906. First, as a designer of automobiles, he developed the Straker Squire Car, then during the War period, he turned to aircraft powerplants. He was awarded the M.B.E. for supervising the manufacture of Rolls-Royce and Renault airplane motors and the re-design and overhaul of a large number of Curtiss liquid-cooled engines. During the latter part of the War he began development of the "Jupiter" engine, and, when the Bristol Aeroplane Co. took over the design and patents in 1920, he joined them as chief engineer of the engine department. Since then he has supervised the production of several successful types of poppet-valve engines, culminating in the "Mercury" and "Pegasus" series. He has been doing valuable research work on sleeve-valve engines during the past ten years. Mr. Fedden is chairman of the 1937 Manly Memorial Medal Committee and an active member of the SAE Overseas Relations Committee. He is also vice-president of the Royal Aeronautical Society and a member of the Council of the Institution of Mechanical Engineers.*

• A. T. Gregory *had nine years of practical experience in the aircraft field as machinist and draftsman with Wright-Martin Aircraft Corp., before entering Stevens Institute of Technology in 1926. While at college he spent his summers working in the test department of Wright Aeronautical Corp. His work at Stevens won him a three-year fellowship to study Diesel engines in Germany. He received his doctorate in engineering at Munich in 1933. Returning to America he again joined the staff of Wright Aeronautical as test engineer, continuing in that capacity until 1935 when he left to become chief engineer of the Ranger Engineering Corp.*

• Eastman N. Jacobs *has made many contributions to aerodynamic research, the principal of which lie in the development and application of improved airfoil sections to airplane design and in systematic studies of wing-body interference. He was Wright Brothers Medalist in 1933 and in 1935 was guest speaker at the*

(Continued on page 25)

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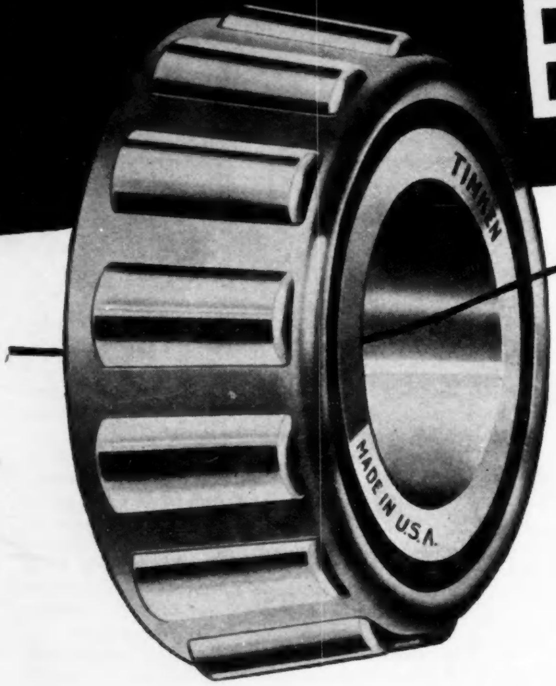

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TAPERED ROLLER BEARINGS

Trend of Air-Cooled Aero Engines –The Next Five Years

By A. H. R. Fedden
The Bristol Aeroplane Co., Ltd.

THE author has written an addendum to his paper: "Future Research on Air-Cooled Aero Engines" delivered in July, 1935.

General prophesies are made on airplane performance, types, trends on the number of engines per airplane, engine sizes in airplanes, wing loading, and engine arrangement. His analysis of engine types to complete the desired power range indicates a definite trend toward higher powers The advantages of the use of higher octane fuels are stressed.

Mr. Fedden deplores the fact that no development work on compression-ignition aircraft engines is being done in England, and thinks that the 1500-hp. class should be tackled energetically.

The comparative qualities of various engine types are discussed.

Negative cooling drag is claimed to be possible at airplane speeds of 400 m.p.h.

The flat engine is mentioned as a possibility although its use depends on the thickness of the airplane wing.

Advice from the airplane designer is considered necessary on wing-thickness trends and other aerodynamical matters to assist in the proper selection of engine types.

SINCE my last paper before this Society, much water has flowed under the bridges and we have entered into a period of intensive activity and development in aeronautical matters not envisaged at that time.

This intensive activity will, undoubtedly, bring new developments to fruition much more rapidly than contemplated in the past and, for this reason, it has been considered that a useful purpose would be served in endeavoring to outline the trend of future air-cooled powerplants for aircraft for the next five years.

This period has been chosen because it is presumed that these engines would be designed as a result of the experimental work already completed or being carried out at the present time, and with the object of meeting the more searching requirements demanded by the results of this increased activity.

It is not claimed that this paper is a highly technical commentary or a definite, precise program of what the immediate future may hold out for the air-cooled aero engine, but rather it is intended to put forward "feelers," on a logical and common-sense basis, of what may reasonably be accomplished within the time under review, with the idea of promoting a discussion on the subject. It is appreciated that any such review must be purely an estimate, admittedly based on European conditions, and conclusions drawn from a set of assumptions leavened by the results of current research work. Such an opinion is certainly open to any amount of conjecture and criticism, but the very fact that at least four years are necessary to develop an entirely new type of aero engine from its original conception, through its teething troubles, to the production stage, would seem sufficient justification for such a review, and to be a subject of paramount importance, worthy of attention and discussion on the broadest possible basis.

Moreover, there are certain other aspects of recent aircraft development which make the task of the right selection of type by the air-cooled aero-engine designer a matter of greater importance than ever before. A considerable step-up in performance, generally, and a greater cleanliness of design of all categories of aircraft have given rise to the necessity for "horses for course" in the form of specialized engines. The day of the general-purpose engine, except for certain civil aircraft requirements, is fast disappearing.

Some years ago an aircraft powerplant could be developed successfully without a very close touch or intimate knowledge of the trend of aircraft requirements, but little hope of success can be held out for such a procedure today. Previously it was the custom to produce a design of engine from which it was planned to obtain smallish orders for engining aircraft of widely diversified types, and for which it was hoped to build up a sufficient production to justify adequate tooling for fabricated quantity production. Similarly, engines were launched into production on a comparatively low horsepower rating, with the avowed intention of stepping up output as the necessity arose. I suggest that such a policy is a great deal more difficult today and, in my opinion, will be impossible in the future.

[This paper was presented at the Semi-Annual Meeting of the Society, White Sulphur Springs, West Va., May 4, 1937.]

TYPE.	MAXIMUM SPEED M.P.H.	CRUISING SPEED M.P.H.	CRUISING RANGE.
CIVIL			
LAND MACHINES.	275	220	1000-1500 MILES
SEAPLANES.	250	200	1500-2000 MILES
SPECIAL CATEGORY LONG RANGE MACHINES.	250	220	3000-4000 MILES
MILITARY			
DESTROYERS.	425-450	–	1½-2 HOURS
MULTI-PLACE FIGHTERS.	400	–	1½-2 HOURS
MEDIUM BOMBERS.		300	6 HOURS
HEAVY BOMBERS.		275	8 HOURS
SEAPLANES.	270	220	10 HOURS

Fig. 1 – Probable Main Aircraft Categories

The improvements in fuels and the more exacting requirements of aircraft demand a full-blooded series from the inception of the type. The hope of reward, if entirely successful, is greater than in the past, but the line of demarcation between accomplishment and failure is a narrower one.

It is believed that, with the march of progress and as the development and bringing to fruition of an aeroplane engine becomes a more and more expensive and prolonged undertaking which, in my opinion, is inevitable, it will be impracticable to make changes in design as rapidly as in the past and, having chosen a type and carried it through to the production stage, it may have to remain unaltered over a longer period than has been normal practice in the past. These trends emphasize the vital necessity of a wise choice when a new design of engine is in the project stage, and the importance of adequately weighing it from all angles and of spending as much time as possible on its analysis on the drawing board before deciding to transfer it to the "flesh."

Assuming that these assumptions are correct, I believe that the aircraft designer may hope for a more specialized and highly developed product in the future, but he may have to be content to make use of a given type of engine for a longer period with comparatively little or no development unless competition is so severe that more rapid changes are made feasible. It is believed that the cost of development of the modern high-efficiency aero engine is not very likely to enable this condition to come about.

This short introduction is intended to serve as the *raison d'être* of this paper, which it is hoped will provide a useful discussion and act as a guide to the engine designer as to the trend of air-cooled aero engines for the next five years.

Types of Aircraft

Before attempting to analyze the layouts of new air-cooled powerplants, it would seem advisable to endeavor to envisage the most important types of aircraft for which these engines will be required, and approximately the speed and range that may be expected from them.

I realize that to attempt such a task may appear extremely rash, especially when the information emanates from the powerplant camp but, if I am correct in my introductory remarks, this new vintage of engines is crying out for some such review and, without it, the task of the engine designer is a very difficult one. Several examples have been seen, of recent years, of perfectly good aero engines having been designed and made which fill no useful field owing to the engine designer having had an incorrect original conception.

I would like to say that these projected categories and speeds of aircraft are deduced entirely on my own responsibility as the result of general observation, and may be thought to be too conservative, but I cannot but believe that the marked stepping up in performance of different types of aircraft during the last few years must level out and gradually slow up, and that this trend will inevitably result in a somewhat longer period for new development; that we must expect an eventual flattening out of the curve and that, in spite of certain views to the contrary, no very drastic changes in layout of aircraft will be made during the period under review.

In 1933 there arrived the classic Douglas type which was in effect a very sane and logical development, consisting of a clean, low-wing monoplane of comparatively high wing loading, stressed skin structure, and with retractable undercarriage, and cowled radial engines fitted with controllable-pitch propellers, and mounted on the leading edge of the wing. For the purpose of this paper it is assumed that, basically, this type will be continued for some considerable period in variant forms, in larger sizes, and with a greater number of engines, and also in smaller forms – twin engines gradually replacing single-engined machines for all purposes.

It is considered that recent estimates of the possible performance of aircraft in the immediate future have, in certain instances, reached figures which it is by no means certain are in the best interests of aviation. It is suggested that a wiser mental attitude would recognize that there are natural limits to progress at any given stage of development, but would also refuse to regard these limits as immutable and rigid barriers. Development can then be defined as the art of raising the limit of what is possible.

HORSEPOWER	WEIGHT – LBS (WITH STANDARD EQUIPMENT AS PER AM INSTRUCTION E 124 ISSUE 3)
750	820
1150	1250
1550	1550
2000	2100

Fig. 2 – Suggested Sizes of Air-Cooled Aero Engines

If this conjecture is correct, the larger types of aircraft most probably will continue to use engines mounted in one plane in-line on the leading edge of the wing, in arrangements of 4, 6, or 8, according to the size of the machine.

A point worth noting in connection with the mounting of a number of engines on the leading edge of the wing is that, for the higher powered categories, in order to obtain the necessary thrust for take-off, a low reduction gear to the engine, and a larger diameter propeller will be necessary. This arrangement means that the engines will have to be comparatively widely spaced. The necessary clearance for propellers of 1500 to 2000 hp. with 0.35 to 0.38 reduction-gear ratios may produce quite a serious problem, so far-reaching and fundamental that it may actually affect engine design to the extent of a larger number of units being chosen for a given total of horsepower by the aeroplane designer or, alternatively, two-speed gears in conjunction with controllable-pitch propellers, or double-concentric propellers. It would be most helpful to hear aircraft designers' views on this subject because it so fundamentally affects engine layout.

It is understood that aircraft designers are awaiting the results of some important research work, affecting wing sections and their characteristics, which may have a far-reaching effect on engine design and which is in course of being investigated at the present time. It also is understood that wing loadings of 30 to 40 lb. may be expected, and speeds in excess

of 400 m.p.h. may be envisaged without coming into the danger zone of the compressibility burble.

However aerodynamically clean aircraft may become in the near future, speeds of this order mean a good deal of horsepower; and a considerable step-up in the unit size of engines as compared with that to which we are accustomed today, must be contemplated.

Although flying at a considerable altitude reduces the specific output required from the powerplant for a given speed, it does not seem possible that stratospheric flying will be current practice within the period under review, except for a few special-purpose military squadrons, and possibly for experimental civil aircraft. The trend of propeller and aircraft design seems to indicate that, at any rate for this stage of development, the engine designer will not have to provide for groups of engines geared to a single propeller, and that single-engined units combined with the normal-type propeller will be more acceptable.

As a basis for discussion, therefore, it is suggested that the main aircraft categories may be divided up as shown in Fig. 1.

Engine Categories to Meet New Aircraft Demands

Assuming that the types suggested in the preceding section cover the main requirements of civil and military aircraft for five years ahead, I propose in this section to suggest the sizes and weights of engines to cover this range of aircraft.

It is not intended to attempt to cater to the smaller civil categories – sports, private, training, or feeder types – not because I think that these are unimportant or uninteresting groups, but because it is considered that they are quite a separate section which should be dealt with apart from the large civil and military types of aircraft.

As I have already suggested in this paper, I am of the opinion that the new vintage of engines will require more time and money spent on their development than previously, and it is, therefore, more important to try to keep down the number of types as far as possible, and I hope to be able to cover the suggested range of aircraft by four sizes of engines, as shown in Fig. 2.

These weight figures are for the bare engine with standard fixed equipment.

Fuel

Fuel is undoubtedly still one of the most important subjects affecting the future development of air-cooled aero engines. During the period under review it is understood that there is little doubt that we shall have 100-octane fuel as readily as we have 87-octane today, and it is possible that we may have even better fuel than 100-octane. I gather that the supplies will probably be in the form of iso-octane, and that it may be quite likely that it will be ready in quantities before the engine makers have developed their new engines to make full use of it.

From this fuel in properly designed engines I think that we may expect an increase in horsepower of 25 per cent, with a decrease in consumption of 5 to 7 per cent. This performance should enable a consistent cruising consumption of 0.5 U. S. pt. per b. hp-hr. at approximately 60 per cent of the maximum power rating.

These improvements in fuel for electric-ignition engines will make the case for the compression-ignition engine system even more difficult to substantiate than before. It will make the compression-ignition engine less valuable from a consumption point of view, from the aspect of the volume of fuel consumed, but the price of the fuel will still be considerably in favor of the compression-ignition type of engine.

Events of the last few years have given the gasoline aero engine an enormous advantage over its only competitor and, at any rate for the next few years, I am afraid that the European requirements of military over civil aero engines are likely to be in the ratio of at least 8:1 which, on the face of it, would appear to retard further the advent of the successful compression-ignition engine. Nevertheless the advantages of the greatly minimized fire risk, cheapness of fuel, elimination of radio-interference problems, and the general higher order of reliability that should ensue from the compression-ignition type of engine, are important factors which cannot be overlooked.

Personally I lean to the view that, for long-range night bombers of moderate performance as well as for civil aircraft, there is a great deal to be said for the compression-ignition engine in fairly large sizes, and of not less than 1000 cruising hp. It is impossible, however, to take such a high specific output from a given swept volume from the compression-ignition engine as from the corresponding gasoline engine, but it is practicable to take a higher percentage cruising output from a given size from the compression-ignition engine and, if we are to look to mechanically assisted or catapulted aircraft for the future, then the compression-ignition engine has a better chance of coming into its own.

I have looked into the possibilities of the compression-ignition engine as compared with the gasoline engine on a comparative basis for a 1000 cruising hp., and the main features of each type are shown in Fig. 3. In this figure all prices are based on European conditions; dollar equivalents are taken as $5 per £.

It will be noted that the lower specific fuel consumption of the compression-ignition engine results in a total consumption per hour of 45 U. S. gal., as against 59 U. S. gal. for the 100-octane engine at similar cruising power and an incidental, but none-the-less important, advantage of the reduced consumption of the compression-ignition engine is the economy to be effected in weight and size of tanks.

In an endeavor to demonstrate the economies in fuel charges to be expected from the compression-ignition engine, I have shown figures for the fuel cost per hour cruising for the two engines under consideration. It has been assumed that the

		100 OCTANE PETROL ENGINE	COMPRESSION-IGNITION ENGINE
HORSEPOWER AT MAX. R.P.M. & RATED ALTITUDE. (5000 FT.)		1500	1500
CRUISING B.H.P. AT 66⅔% MAX. POWER.		1000	1000
CRUISING CONSUMPTION.	LBS/B.H.P./HR.	·435	·38
	PTS/B.H.P./HR.	·47	·36
	GALLS./HR.	59·0	45·0
NETT DRY WEIGHT - LBS.		1620	2100
WEIGHT PER B.H.P. - LBS.		1·08	1·4
FUEL COST PER HOUR BASIC PRICES:- 100 OCTANE 2/6 FUEL OIL 1/2 PER GALLON.	(a) NO TRANSPORT CHARGE	£7-7-6	£2-12-6
	(b) 1/6 PER GALLON TRANSPORT CHARGE	£11-16-0	£6-0-0
	(c) 2/6 PER GALLON TRANSPORT CHARGE	£14-15-0	£8-5-0
SAVING IN FUEL COST PER HOUR.	(a) NO TRANSPORT CHARGE		£4-15-0
	(b) 1/6 PER GALLON TRANSPORT CHARGE		£5-16-0
	(c) 2/6 PER GALLON TRANSPORT CHARGE		£6-10-0

Fig. 3 – Comparison of 1500-B.Hp. Air-Cooled Radial Engines – 100-Octane and Compression-Ignition

basic cost of 100-octane fuel, without transport charges, would be 2/6d per imperial gal. (52 cents per U. S. gal.), and for fuel oil, 1/2d per imperial gal. (24 cents per U. S. gal.). These figures are, of course, purely arbitrary and must be taken solely as my own opinion as to what the relative costs may be in the next 5 years. In deciding on these relative costs, I do not think that the compression-ignition engine has been favored at all. Three cases have been taken for relative cost – (*a*) with no transport charge, (*b*) assuming 1/6d per imperial gal. (31 cents per U. S. gal.) transport charge, and (*c*) assuming 2/6d per imperial gal. (52 cents per U. S. gal.) transport charge, with a view to representing probable costs in undeveloped countries where the transport of fuel becomes exceedingly expensive.

If we consider the case of two four-engined machines of 72,000 lb. all-up weight, and a power loading of 12 lb. per hp., one having 100-octane gasoline engines and the other having compression-ignition engines, each with the characteristics as outlined on Fig. 3 then, of the two graphs shown in Fig. 4, Graph *A* indicates the payload for a given flying time under cruising conditions. From this curve it will be seen that the compression-ignition engine is at a disadvantage for flying times below 9½ to 10 hr., at which point the payload is approximately 15,000 lb. representing 20 per cent of the all-up weight.

At the Atlantic range of 2500 miles against a 40 m.p.h. headwind, it will be seen that the payload is 1500 lb. greater with the compression-ignition engine.

Graph *B* of Fig. 4 is derived from Graph *A* and indicates the effect on range for a given payload when using compression-ignition engines in place of 100-octane gasoline engines.

The vertical line on this curve is drawn at the point where the payload is equal to that for the aircraft with 100-octane engines equipped for the Atlantic range, and it will be seen that, for a similar payload, the compression-ignition engine would give an increased range of 200 miles.

It is interesting to note the enthusiasm and activity shown toward the production of the compression-ignition aero engine on the Continent of Europe and to speculate on the reasons for this interest.

I can raise no enthusiasm for the theory of a ray to cut out the magneto of a spark-ignition engine, nor can I foresee any real difficulty in producing considerable quantities of gasoline of a reasonably high octane value.

There is no doubt in my mind that there is a considerably decreased fire risk when employing compression-ignition en-

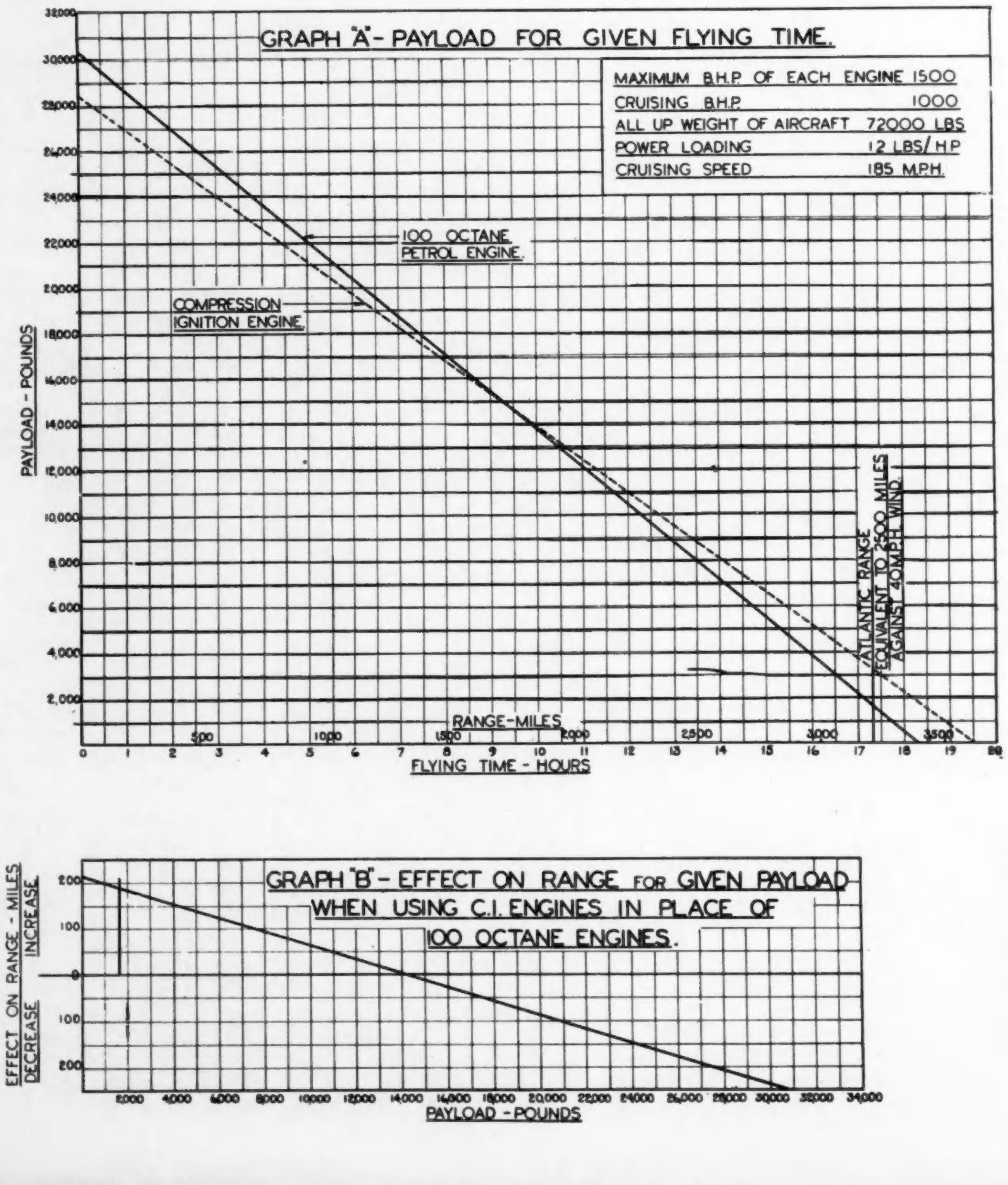


Fig. 4 – Comparative Curves for Four-Engined Aircraft Fitted Alternatively with 100-Octane Gasoline Engines and Compression - Ignition Engines

gines in aircraft, especially when compared with 100-octane engines where much closer cowling and higher specific output will increase the chance of fire if the engines are running at the time of a forced landing because everything inside the cowling will be considerably hotter than was the case in the earlier type of gasoline-engine installation. Fire risk as the result of a crash of an aircraft cannot be considered of real military importance, but it is interesting to speculate on the respective chances of aircraft being set alight while in the air when powered alternatively with a gasoline or heavy-oil engine.

I much deplore the fact that greater energy is not being applied to the problem of the compression-ignition engine for aircraft in England today. In the past, official support has been given to compression-ignition research, and The Bristol Aeroplane Co., amongst others, has undertaken a considerable amount of experimental work along these lines, but unfortunately the progress of the gasoline engine has been so rapid that, up to the present, it has not been deemed advisable to carry these efforts beyond the embryo stage.

I believe that my estimates for the compression-ignition engine are conservative and, assuming that these figures are correct, it would be interesting to know from aircraft designers what is considered to be the value of such a type of engine.

Engine Layouts from the Geometric Aspect

In this section it is proposed to discuss some of the most important items governing the geometric layout of air-cooled powerplants.

Many factors contribute to the design and form that air-cooled aero engines may take, included in which are power, prime cost, weight, balance, firing order, distribution, fuel consumption, accessibility, and maintenance; all play their part and cover what I shall term for the purpose of this paper, the geometric layout. Cooling drag, and bulk or wetted surface, I shall term the aerodynamic layout, and this layout is dealt with in the next section.

As a result of a talk with T. P. Wright last fall, I had hoped to be able to produce a figure of merit for the various types of aero engine at the recent Paris Salon but, after due deliberation, I have been persuaded that this method is not feasible; so many factors have to be brought into such a formula that it would become impracticable.

Before proceeding to talk of the future, it may be instructive to look back on the past, and Fig. 5 shows the state of affairs at the last three Paris Salons. Although this tabulation is interesting and there are some lessons to be learned from it, it cannot be taken too literally, but merely as a guide as to the trend for the future. As mentioned in the previous section, the small sizes of engines are omitted from this tabulation. This chart shows a steady increase in the percentage of air-cooled engines, and that the radial air-cooled engine is holding its own. It is interesting to note that the percentage of engines between 500 hp. and 750 hp. has decreased, whilst an increase is shown in the 750-hp. to 1000-hp., and the 1000-hp. to 1300-hp. classes. This trend is, to some extent, due to the development of existing types and to the use of better fuels. It also serves to demonstrate the general tendency for increased power. It is pointed out that the figures for the 1936 Paris Salon are bound to be somewhat incomplete owing to the absence of German and Italian exhibitors.

Power is obviously dependent upon the required performance of the aircraft and, in the present state of the art, it would appear that to employ cylinders of more than 5¾-in. to 6-in. bore introduces very serious problems, and it will therefore be appreciated that, when we approach the higher categories of power, namely, 2000 hp., it is difficult to find a geometric layout, even with the largest size of cylinder, that will give us the required power, and still remain a reasonably simple production proposition.

We will consider the question of cost, ease of production, and weight together, as all of these factors may be grouped conveniently. Low first cost, ease of production, speed of removal and re-installation, are all agreed to be important to the civil airline operator, but it is felt that comparatively little attention is at present paid to them for military purposes. The present Air Ministry expansion scheme has emphasized the vital necessity for due consideration being given to such problems. There is little doubt that ease of production of a straightforward design by relatively unskilled labor is a factor which must be regarded with due importance, and that aircraft constructors must be encouraged to give the fullest consideration to those types at the expense of others which are more difficult and expensive to produce, unless the latter types offer very considerable advantages from the aspect of performance. Fewness of parts, light weight, and symmetrical layout certainly contribute towards low cost and ease of production.

Fig. 5 – Paris Salon – 1932-34-36 – Analysis of Air-Cooled Engine Exhibits Over 500 B.Hp.

	1932	1934	1936
AIR COOLING	42%	50%	69%
LAYOUTS			
RADIAL	100%	95%	95%
OTHER TYPES	-	5%	5%
RATINGS			
500-750 B.H.P	89%	69%	45%
750-1000 B.H.P	11%	26%	33%
1000-1300 B.H.P.	-	5%	22%

On general principles, therefore, the greater the number of cylinders per unit volume, the greater the weight; and the smaller the volume of engine, the higher the specific output of horsepower that may be expected. These claims are illustrated graphically in Fig. 6 which provides a composite series of graphs taken from plottings of a number of different engines, and illustrates the lightest practical form of engine for any given horsepower, and the effect of cylinder capacity and total volume on specific output.

The series of short curves compare weight and horsepower for different types of engines, the dotted lines being for 87-octane fuel and the full lines for 100-octane fuel. It will be noted that the 100-octane nine-cylinder engine is the lightest type of engine and, in this case, it has been carried up as far as 1200 hp. to illustrate the argument. The dotted line shows the 87-octane nine-cylinder carried up to 1000 hp. The fourteen-cylinder double-bank radial – 87-octane with dotted line, and 100-octane with full line – is the next lightest series shown, and powers are carried up to 1500 and 1750 hp. respectively.

The flat twelve-cylinder 87-octane engine, will be seen to be heavy, and is shown carried up to 1350 hp. The flat twelve-cylinder 100-octane engine is a good deal better, and is shown carried up to 1550 hp.

As regards the in-line multibank engine, I have only attempted to deal with the twelve-cylinder flat in-line engine in this group of curves, because such engines as the twenty-four-cylinder "cross" type, in the higher powers, would be even less favorable in regard to weight per brake horsepower.

The last curve of the group shows the weight advantages of the radial in the higher powered categories.

Turning now to the two large curves of Fig. 6 and starting with the one in the bottom right-hand corner, comparing brake horsepower to brake horsepower per liter, it will be seen that, with the quite small engine of less than 100 hp. (and for the purpose of this curve the examples are not, of course, aero engines, but special racing motor car and motor bicycle engines) the output goes up as high as 140 to 150 hp. per liter. As the total power of the engine is increased, so the output per liter goes down, until, for a 2000-hp. engine, it has

dropped to 37. Turning to the other curve, starting at the left-hand bottom corner, dealing with brake horsepower measured against liter capacity, it will be seen that, whereas 1000 hp. may be expected from just under 20 liters, to obtain 2000 hp. it will be found most economical to go to 55 liters. It is suggested that these last two curves shed interesting light upon why it is so difficult to produce a successful large-size aero engine, weight considerations necessitating the largest bore and stroke permissible, the latter resulting in a lower rotational speed.

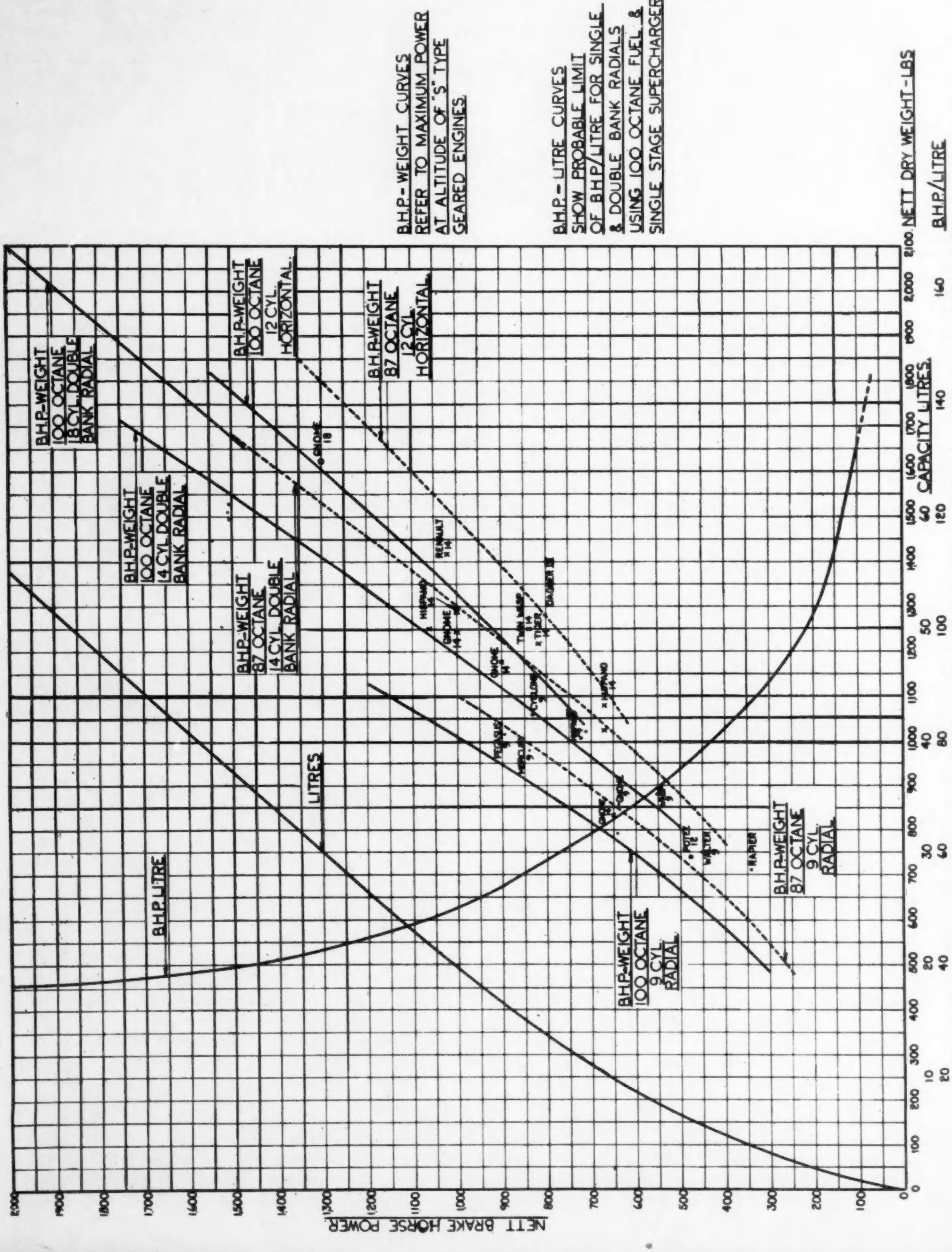
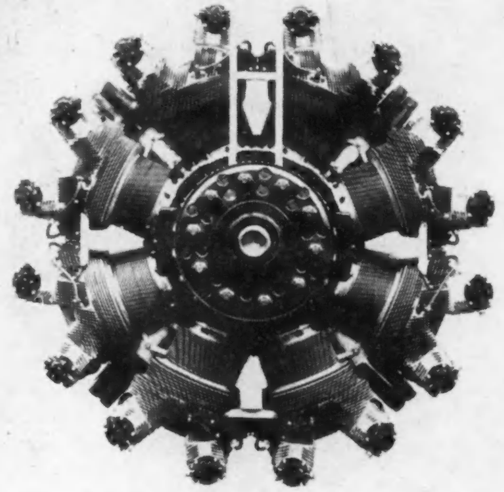
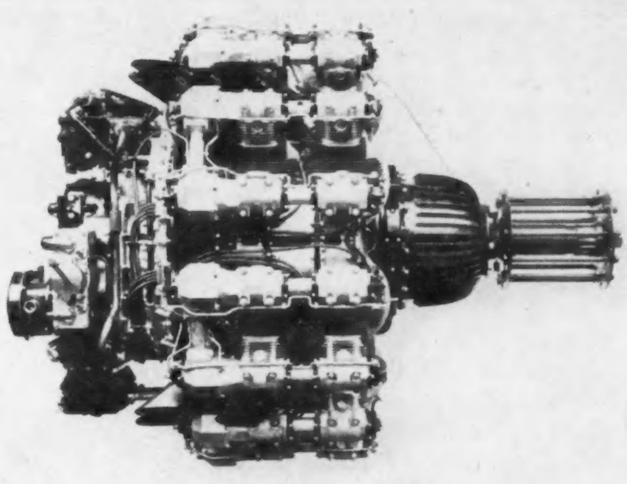


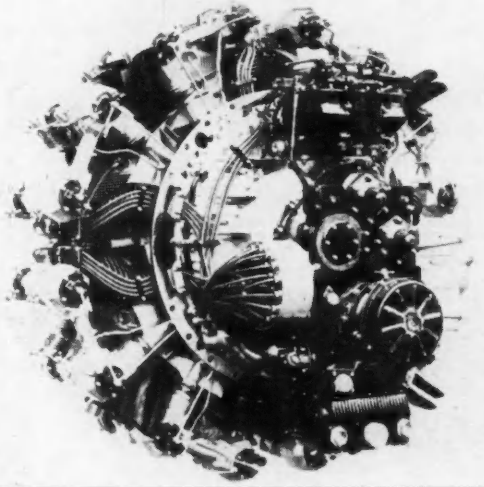
Fig. 6 – Curves Showing Weight – B.Hp. Liters – B.Hp. and B.Hp. per Liter for Various Types of Air-Cooled Engines





16 CYLINDER AIR COOLED DOUBLE OCTAGON ENGINE

SWEPT VOLUME - 25·7 LITRES (1570 CU.INS) NET WEIGHT - 1460 LBS.



FUEL OCTANE VALUE	R.P.M.		COMPARATIVE PERFORMANCE							
			'M' TYPE ENGINE				'S' TYPE ENGINE			
	NORMAL	MAXIMUM	TAKE OFF		ALL OUT LEVEL		TAKE OFF		ALL OUT LEVEL	
			B.H.P.	LBS/BHP	B.H.P.	LBS/BHP	B.H.P.	LBS/BHP	B.H.P.	LBS/BHP
73	3000	3450	850	1·72	870 AT 6000'	1·68	780	1·87	840 AT 13,500'	1·74
87	3000	3450	1040	1·4	1020 AT 6000'	1·43	900	1·63	1000 AT 15,000'	1·46

7

Fig. 7 – Sixteen-Cylinder Air-Cooled Double Octagon Engine

As a complement to the series of composite graphs just illustrated, the following figures are instructive:

Fig. 7 shows three views and a tabulation of a double-row sixteen-cylinder engine produced by the Bristol Aeroplane Co. in 1931. This engine was designed to run at high speed and with overhead camshafts, but was abandoned chiefly due to the Bristol Aeroplane Co.'s sleeve-valve development. It shows clearly, however, how easy it is to add weight, with an increase of revolutions per minute, and a relatively large number of cylinders, for a given swept volume.

Fig. 8 shows three views of a model of a twenty-cylinder multibank radial of 1000 hp. with overhead camshafts, designed, but not actually made, by the Bristol Co., for a similar type of high-speed high-efficiency engine, and it will be noted that the power-weight ratio of this type of engine is also disappointing.

Fig. 9 shows a model of a flat engine to be buried in the wing, with a tabulation of the power and weight, to meet the first and third categories.

Fig. 10 shows the Potez-Lorraine twelve-cylinder flat engine which was exhibited at the 1936 Paris salon. Although this engine does not appear to have been designed for a minimum depth with a view to burying it completely in the wing, it is possibly an indication of the trend of future design for really high-speed aircraft of the smaller category. The weight/brake horsepower of this engine is surprisingly low for an in-line layout as will be seen from the tabulation.

Fig. 11 shows the Walter Sagitta twelve-cylinder inverted vee engine, which is a good representative type of the moderate-power twelve-cylinder vee engine popular on the Continent. Its overall dimensions and weight/brake horsepower show the disadvantages of the in-line type in comparison with the radial. The silhouette of the proposed cowling for this engine emphasizes the abnormal wetted surface of this type, which matter I shall refer to again later on in the paper.

Output per liter is often considered to be the all-important criterion of engine efficiency. Fig. 12 is shown to illustrate that this factor can be somewhat misleading. A tabulation of different types of engines is given on an output per liter basis, and also on a power output per square inch of piston area. It will be seen that this latter figure is a more valuable guide as to the actual output efficiency of an engine as it is proportional to the product of mean pressure and piston speed. It will be noted that some engines of high output per liter, owing to their short stroke and low piston speed, are not actually producing as much useful horsepower per square inch of piston area as other types with a lower output per liter. Piston speed, as shown in the last column of Fig. 12, is another important problem to explore when reviewing the geometric layout of engines and, although it is not a truly accurate measure of inertia pressures of either pistons or valve gear, it nevertheless is the best criterion of mechanical and breathing difficulties due to velocity.

Balance, firing order, and distribution, are three important factors in the success of a smooth-running and satisfactory aero engine, and are governed by the mechanical layout, the first

two being determined by fixed mathematical principles, and the third factor by a combination of timing and supercharging conditions.

Fuel consumption is an important factor and is governed by a wide variation of conditions, including the thermodynamic qualities of the cylinder design, valve timing, blower efficiency, distribution, and engine speed. Consumption is also dependent upon the quality of fuel and, since an up-to-date and efficient aero engine cruising at 70 per cent of its power, burns its own weight of fuel in three hours, the importance of this matter should be fully realized.

Accessibility and maintenance are mechanical features affected by the fundamental layout, and I shall have something further to say about accessibility later on in this paper.

When considering the geometric layout of engines, therefore, it is suggested that we must not let our enthusiasm for too small cylinders run away with us. Any move in this direction is always accompanied by a corresponding increase in weight and cost of production, and I think we may conclude from this review that, for a given horsepower, we should aim at having the fewest number of cylinders as possible commensurate with smooth torque, satisfactory cooling, even distribution, and reasonable mechanical balance.

To cover the four different categories of engine powers suggested as being required for the period under review, it would appear that the most promising layouts will still be divided into two families – radial engines single and double bank, and in-line multibank.

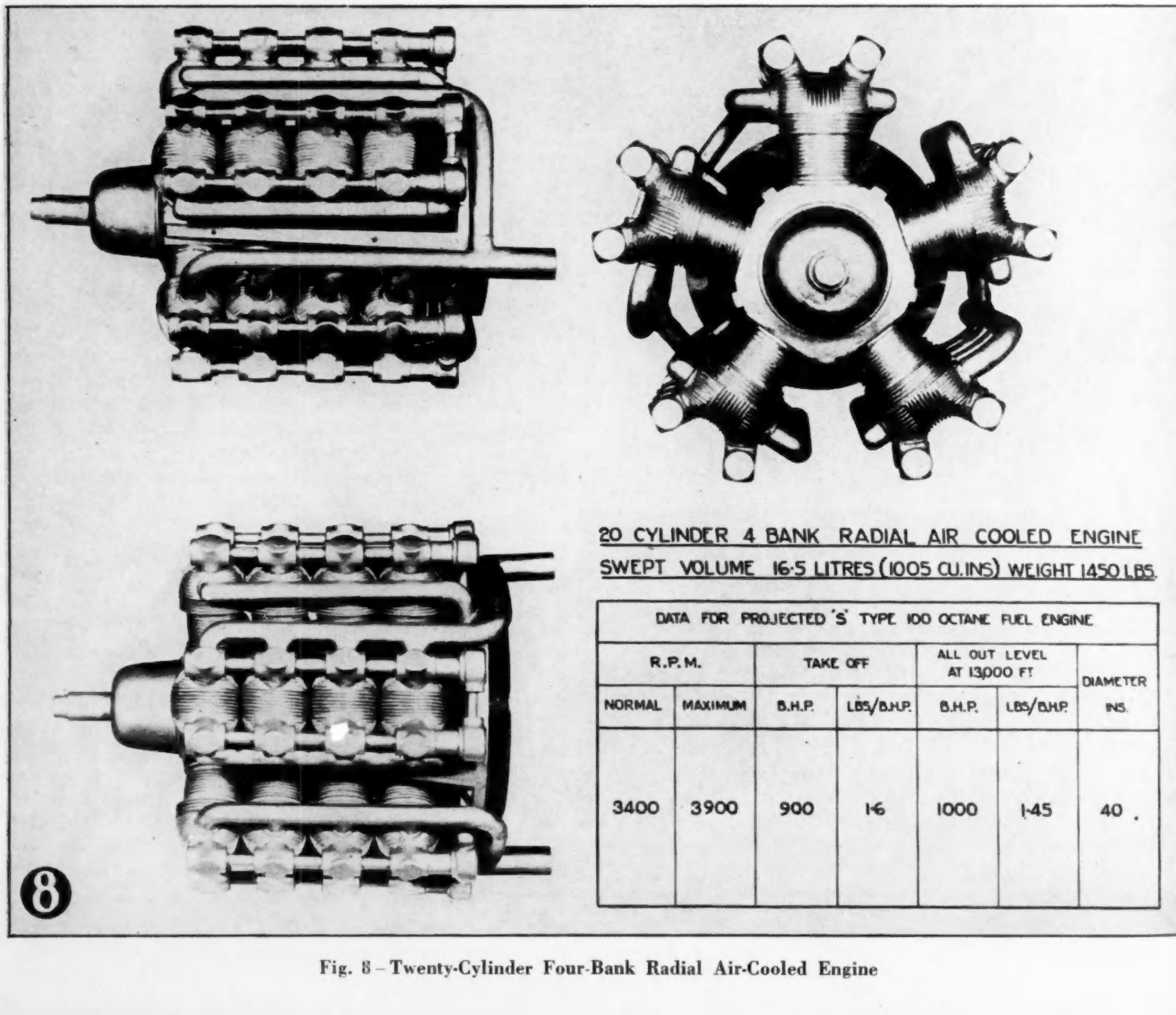
Fig. 13 is a somewhat ambitious attempt to assess the relative merits of the more conventional layouts of air-cooled engines from the geometric aspect for the powers we require, and it is suggested that the increased weight and cost of production of the in-line engines will be sufficiently serious to militate against their introduction for the immediate future, except under special conditions, which will be dealt with later on in the paper.

No attempt has been made to illustrate graphically, power, balance, firing order, distribution, and fuel consumption, it being agreed that balance and firing order are satisfactory on all the types considered and that fuel consumption should be generally similar, but tending to become lower as the number of cylinders are increased, provided cooling technique is adequate. It should be possible to make distribution reasonably good on all these types, but it seems fair from experience to favor the radial engine on this score in view of the shorter and more symmetrical pipes.

Engine Layouts from the Aerodynamic Aspect

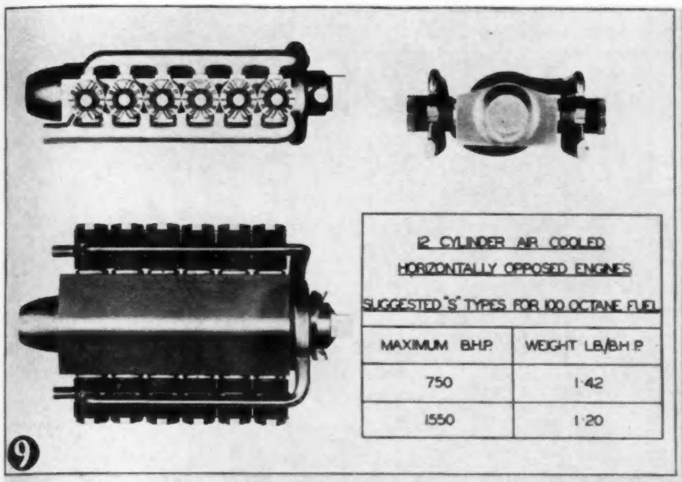
The layout of future air-cooled aero engines from the aerodynamic aspect embraces a review of the various factors affecting the drag of the complete engine installation.

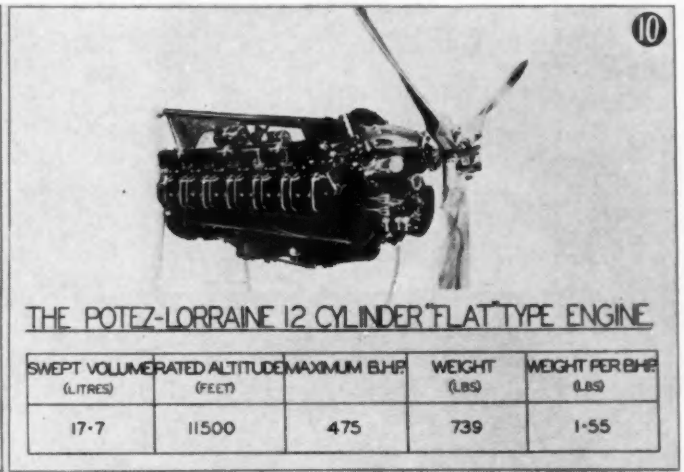
The main governing factors in aerodynamic layout are shape, overall size or wetted surface, and wing surface as a



DATA FOR PROJECTED 'S' TYPE 100 OCTANE FUEL ENGINE						
R.P.M.		TAKE OFF		ALL OUT LEVEL AT 13,000 FT		DIAMETER INS.
NORMAL	MAXIMUM	B.H.P.	LBS/B.H.P.	B.H.P.	LBS/B.H.P.	
3400	3900	900	1·6	1000	1·45	40

Fig. 8 – Twenty-Cylinder Four-Bank Radial Air-Cooled Engine





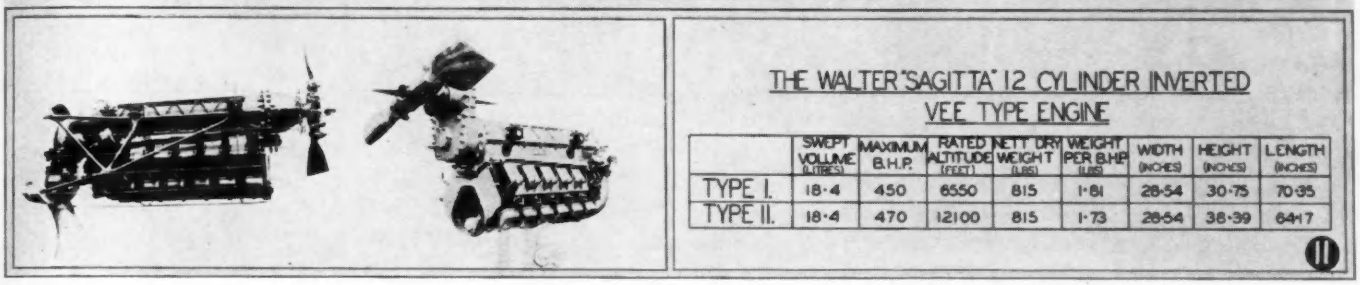


Fig. 9 – Twelve-Cylinder Air-Cooled Horizontally Opposed Engines
Fig. 10 – The Potez-Lorraine Twelve-Cylinder "Flat"-Type Engine
Fig. 11 – The Walter "Sagitta" Twelve-Cylinder Inverted Vee-Type Engine

function of the complete nacelle including the powerplant. These factors are becoming increasingly important as aircraft speeds rise, and will require the closest cooperation in the future between aircraft and aero-engine designers, in fact, for the smallest and highest speed categories of military machines under consideration, I venture to suggest that, within the period under review, a specialized type of engine will have to be produced.

Until quite recently it was accepted as a fact that any heat-dissipating apparatus entailed an increase of head resistance, and that the drag due to an engine installation was often assumed to be proportional to the frontal area of the engine plus its cooling system. Fortunately, the advent of ring cowling for the radial engine was the beginning of the end of this fallacy, and recent research work at the Royal Aircraft Establishment has shown that, for overall aerodynamic efficiency, there is little to choose between the best representative types of powerplant, the variation of the relative drag contributions from different sources balancing out evenly. At the same time it is believed that there is scope for improvement along certain lines of development in each class.

The drag of a power unit can be broadly divided into three headings:

(*a*) *Drag due to cooling air flow.* – Basically, for any cooling system, a certain weight of air per minute is required. So far as air-cooled engines are concerned, this weight is a function of cylinder size, fin area, and power output. From this aspect, therefore, there are two distinctive types of layout:

(1) The in-line having a relatively large number of small cylinders which favor a reduced mass flow (being the equivalent of an increase in radiator size) at the expense of a higher weight-per-brake-horsepower ratio.

(2) The radial with fewer, but relatively larger, cylinders, requiring a slight increase in mass flow, but favoring the lowest weight-per-brake-horsepower ratio.

To illustrate the magnitude of the mass-flow factor on radial engines, tests have been carried out on an unbaffled Bristol Pegasus-type cylinder, which show that the cooling power loss only varies as the power output, raised to the 2.4th power. Since there is no indication that the limit of finning has been reached, this exponent may be reduced by improved technique and development of baffles.

Fig. 14 shows curves, based on these test data, in which the cooling power loss, expressed as a percentage of the brake horsepower, has been plotted against the brake mean effective pressures for different working temperature. The apparatus used did not permit of the actual measurement of cooling power loss, so these curves have been plotted on an arbitrary basis of a 1 per cent power loss at 160 lb. per sq. in. b.m.e.p. for a temperature difference of 200 deg. cent.

An inspection of Fig. 14 clearly shows that, over the recommended range of working temperatures, the effect of cooling power loss with increasing brake mean effective pressure is

TYPE	CAPACITY (LITRES)	MAXIMUM RATING		BHP/LITRE CORRECTED TO SEA LEVEL	BHP/SQ IN PISTON AREA CORRECTED TO SEA LEVEL	PISTON SPEED (FT/MIN)
		B.H.P.	R.P.M.			
AERO ENGINES						
BRISTOL PEGASUS XXI	28·7	1010	2600	35·2	4·32	3250
BRISTOL MERCURY VII	24·8	840	2750	37·5	3·97	2980
ARMSTRONG SIDDELEY TIGER IX	32·7	880	2375	26·9	2·64	2375
NAPIER DAGGER III	16·8	805	4000	49·6	3·05	2500
ROLLS-ROYCE "R" (SCHNEIDER TROPHY)	36·7	2785	3400	75·6	8·20	3450
PRATT & WHITNEY WASP 1830	30·0	1100	2650	36·7	3·30	2430
WRIGHT CYCLONE "G"	29·8	1000	2250	33·6	3·77	2580
GNOME-RHÔNE 14N	38·6	1000	2400	28·4	3·02	2600
GNOME RHÔNE 14M	18·9	650	3000	37·7	2·82	2280
HISPANO-SUIZA 14AA-00	45·2	1000	2100	22·9	2·52	2340
RENAULT COUPE DEUTSCH 12V	8·0	450	4500	56·5	3·3	2650
AUTOMOBILE ENGINES						
AUSTIN RACING	·744	116	7600	155·8	6·54	3240
TALBOT 3·5 LITRE	3·377	123	4500	36·4	2·63	3310
FORD V8–85	3·62	85	3800	23·4	1·44	2370

NOTE:- IN THE CASE OF ENGINES RATED AT ALTITUDE THE CORRECTED B.H.P.'s WERE OBTAINED BY ADDING TO THE NETT B.H.P. THE POWER A BLOWER OF 50% OVERALL EFFICIENCY WOULD ABSORB TO RAISE THE MIXTURE FROM ATMOSPHERIC PRESSURE TO 14·7 LBS/SQ.IN

Fig. 12 – Engine Comparison on the Basis of B.Hp. per Sq. In. Piston Area

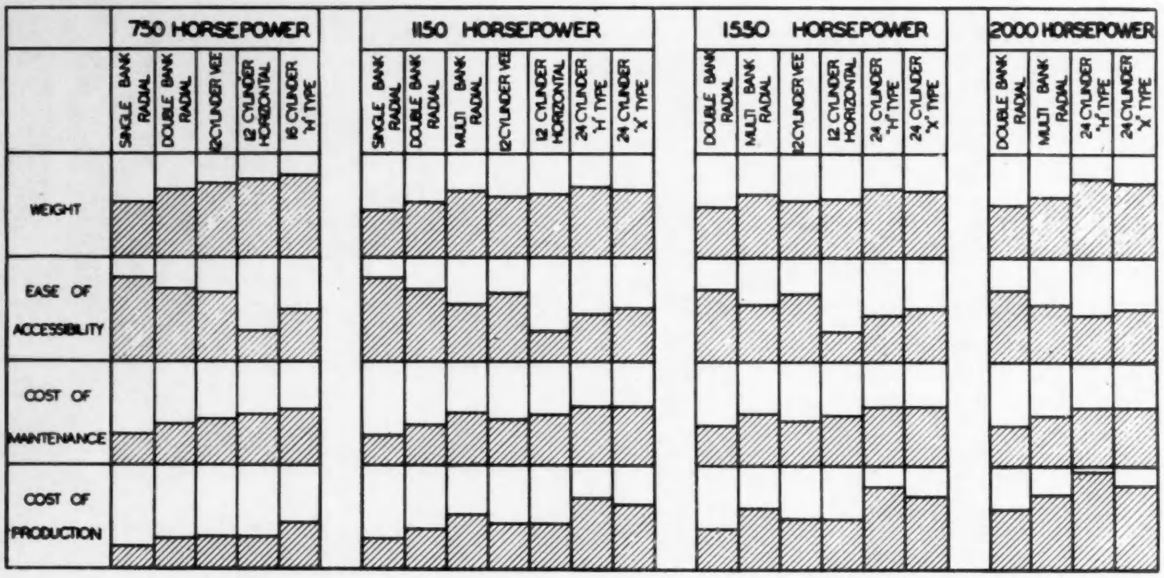


Fig. 13 – Relative Merits of Various Air-Cooled-Engine Layouts

extremely small. The high drag cost of running at too low a temperature is clearly illustrated, and it is interesting to note that a 10 per cent increase in working temperature permits approximately 40 per cent increased power output for the same fractional cooling power loss.

Air density is another factor which affects the rate of heat dissipation. In this connection it should be noted that the fall in air temperature with altitude, up to the lower limits of the stratosphere, is more than sufficient to offset this effect, since Equation (2) on Fig. 14 shows that the cooling power loss only varies inversely as the square of the density, whereas it varies inversely as no less than the 9th power of the temperature difference.

Flight tests on baffled engine installations indicate a slightly

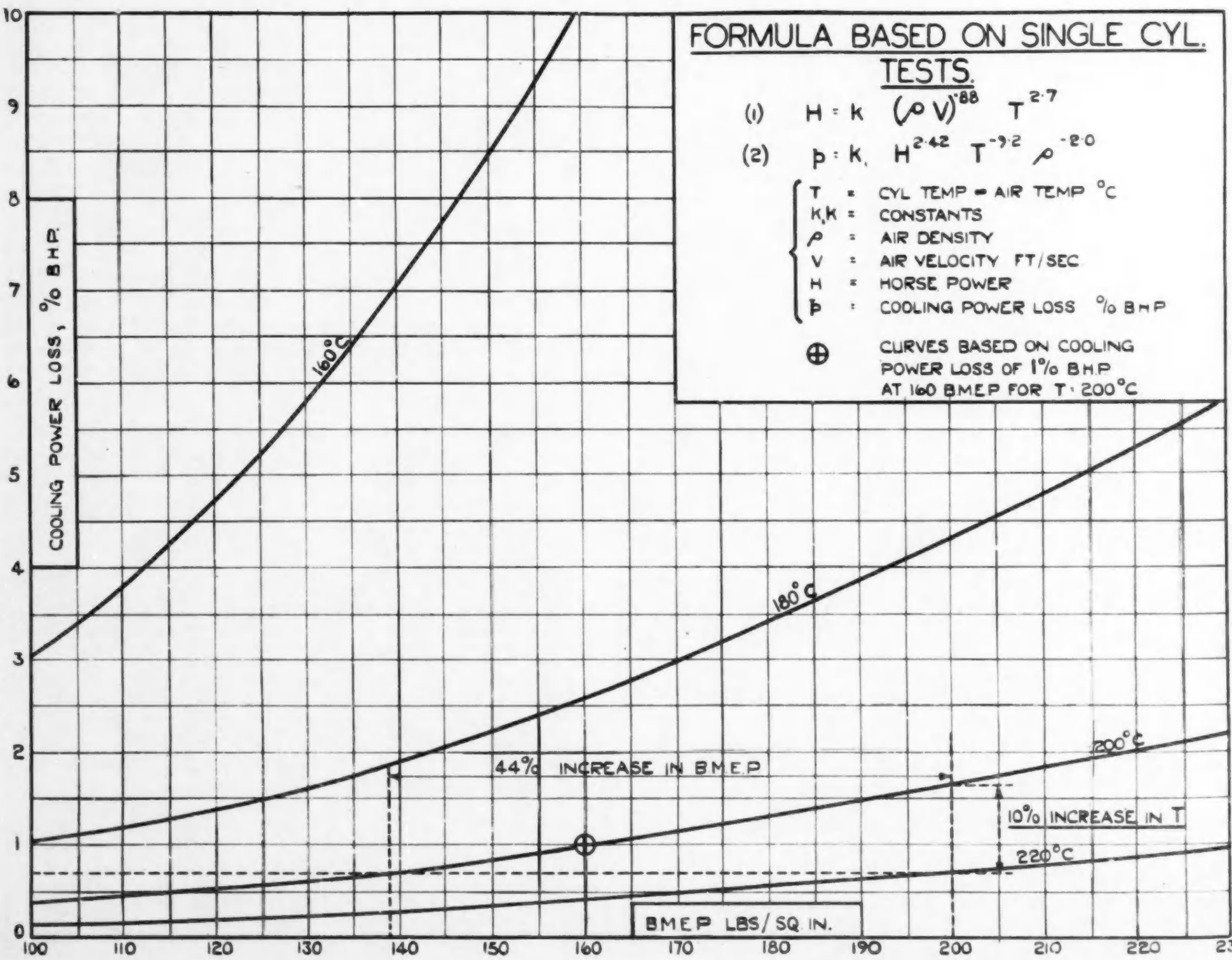


Fig. 14 – Variation of Cooling Power Loss with Increasing B.M.E.P. (Pegasus Cylinder)

lower index of T than that obtained from single-cylinder tests, and Fig. 15 shows variation of cylinder temperatures under level speed conditions with altitude based on this relationship, assuming a constant power engine and fixed gill exit. The three curves represent installations giving different ground-level temperature conditions.

With increased speeds of aircraft, the adiabatic rise in temperature of the cooling air caused by slowing it down over the surface to be cooled, is becoming a factor of considerable importance since it varies as the square of the speed and, whilst being only 9 deg. cent. at ground level at 300 m.p.h., it becomes 16 deg. cent. at 400 m.p.h., and 25 deg. cent. at 500 m.p.h. The high temperature of the cooling surfaces of the air-cooled engine, however, will cause it to be less affected by this consideration than other types.

The effect of the compressibility of air on the performance of high-speed machines is becoming more serious and, for speeds in excess of 400 to 450 m.p.h., may present a new set of aircraft design problems. This effect, however, is not wholly detrimental so far as the powerplants are concerned, as has been demonstrated by Meredith of the Royal Aircraft Establishment who has established that a ducted type of cooling system can function as a heat engine – the heat energy imparted to the air in cooling the engine being converted to an effective thrust by adiabatic expansion. The thrust obtained increases approximately as the square of the speed, and Fig. 16 shows the possible gain in thrust horsepower with increasing speed for a baffled radial air-cooled engine of 1000 hp. The dotted line indicates the theoretical maximum gain on the assumption that the total velocity head is obtained in the plane of the cylinders by reducing the cooling-air velocity to zero, and the full line represents a more practical condition when the "cold" internal cooling power loss is 2 per cent of the brake horsepower. An inspection of this figure shows that, for a total flow of 400 cu. ft. per sec., the drag due to cooling at 295 m.p.h. is offset by an effective thrust and, at 410 m.p.h., there is a net gain which is equal to 2 per cent of the brake horsepower.

Apart from compressibility effects, there is a further gain to be derived by utilizing the kinetic energy of the exhaust gases by reaction in a rearward-facing exhaust pipe. Unfortunately, this gain only varies with machine speed but, even so, it is more than sufficient to offset the losses due to change of momentum of air used for carburetor and oil cooling – which vary as the square of the speed – and still leaves a balance for effective thrust.

In concluding this section, it can be said that the various authorities dealing with this aspect are agreed that, whichever arrangement of powerplant is used, the drag caused by cooling air flow is relatively small, being approximately equal to 1 per cent of the brake horsepower and, under certain conditions, natural physical laws function in such a manner as to reduce the drag from this source, and should in fact tend theoretically to produce an effective thrust.

(*b*) *Drag due to installation of nacelle on a wing.* – Nacelle form and drag are influenced by the shape of the engine, its overall length, and its weight. Broadly speaking, in-line engines are longer than the radial, but have a smaller cross-sectional area.

There are two main problems to be considered under this

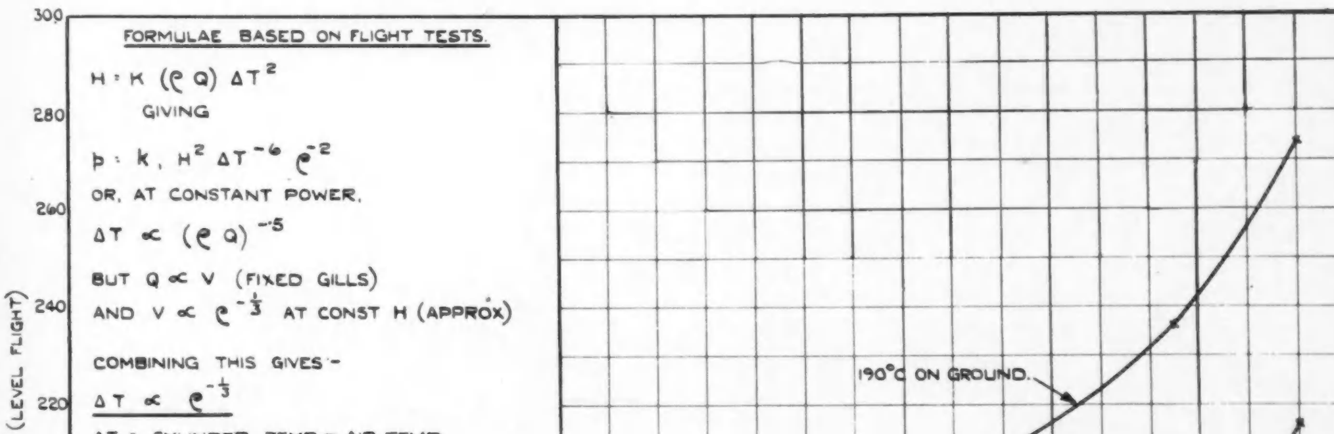


Fig. 15 – Variation of Cylinder Temperature with Altitude at Constant Power Output and Fixed Gill Openings

heading – the reduction of spoiling loss associated with duct entries, and reduction of wetted surface. With regard to the former, the present conventional form of cowled radial engine appears to suffer more than the in-line engine in this respect, a contributory factor being a boundary layer breakaway over the propeller spinner which is in the center of the duct entry.

Tests carried out in the N.A.C.A. wind tunnels on radial air-cooled installations show that, for a given nacelle-wing combination, the maximum propulsive efficiency is obtained with the propeller located at 30 per cent of the chord ahead of the leading edge, and tests in this country confirm this finding for similar geometric arrangements. Research at the Royal Aircraft Establishment also shows that the radial engine nacelle drag is a function of the ratio of wing thickness to engine cowl diameter. As the wing thickness more nearly approximates the cowl diameter, the drag of the nacelle becomes less, mainly due to reduction of spoiling loss.

From a consideration of pitot entries in the leading edge of the wing and provided that the internal wing structure is arranged for duct cooling and accessibility, the drag due to spoiling loss and nacelle surfaces could be practically eliminated by the retraction of the radial engine within the leading edge on aircraft whose wing thickness equals the engine diameter. Existing test data indicate that, if the propeller were required to work within 10 per cent ahead of the chord, its propulsive efficiency would not be affected appreciably. Accordingly, this conception should receive serious attention.

This arrangement will only be possible on aircraft of at least the Short Empire Boat size and proportions and, for the period under review, improvements in detail technique will still be required for a large number of radial-engine installations employing conventional nacelles.

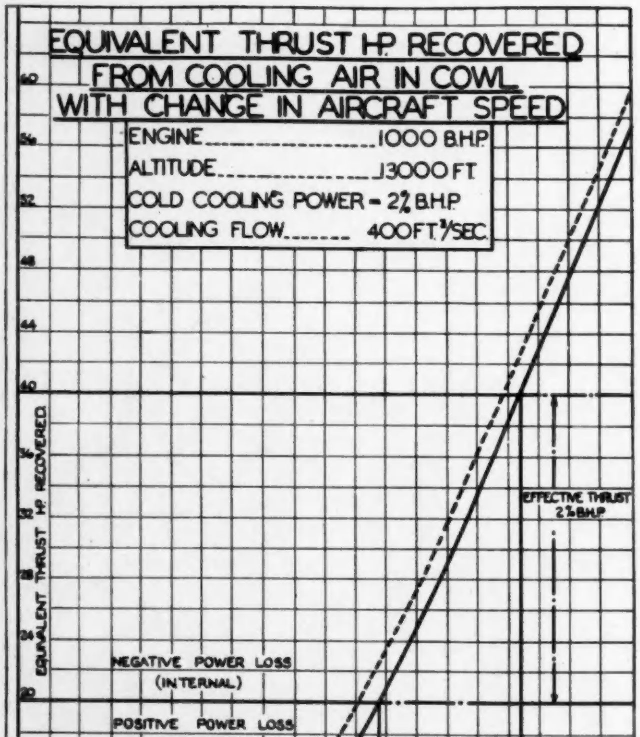


Fig. 16 – Equivalent Thrust Hp. Recovered from Cooling Air in Cowl with Change in Aircraft Speed

To illustrate the relative effect of in-line and radial engine forms on nacelle surface area, I have examined comparative installations on the basis of equal power output and the principal dimensions are given in Fig. 17. The upper drawing shows an in-line and radial engine mounted on a particular wing on the basis of equivalent balance, the radial engine being mounted normally, and the in-line engine being set back in view of its greater weight, to keep the center of gravity of the aircraft in the same position. The lower sketch shows the in-line engine mounted to clear the wing structure. The difference in wetted area additional to wing in the two cases is small, but does in fact favor the radial type.

Fuselage interference effects, and in many cases the housing of a mechanically retracting undercarriage, need careful consideration in deciding upon the design of the nacelle and its position in relation to the wing if the minimum drag is to be achieved, and a compromise generally has to be made after consideration of all the factors involved. Such research as has been carried out on full-scale installations to date indicates a form drag with nacelles irrespective of the type of engine enclosed and, by the reduction of this drag in common with the development of the technique of surface finish on the complete aircraft, there is an appreciable gain to be derived.

It is in this connection that full-scale research can be so useful. There is a fund of information based on model tests relating to the drag cost of mounting a nacelle on a wing from which certain inferences can be drawn, but there is a very urgent need for further full-scale ad hoc research on practical installations for each type of powerplant to confirm how closely in actual practice the technique of design and finish of the manufactured components agree with small-tunnel results.

Until such a connected series of tests is carried out, it will be impossible to assess with complete accuracy the relative drag costs of representative power units mounted on a wing.

There is some evidence to show that, on a radial air-cooled engine, an improvement is to be obtained by deleting the conventional controllable gill exit and ducting the cooling air to the trailing edge of the wing. Fig. 18 has been prepared to show the application of this principle on a double-row installation. The nacelle has been dropped, and provision made for the retractable undercarriage. The lines of the duct are indicated in the plan and elevation of the nacelle; the sections show the passages on either side of the wheel housing. A controllable flap at the exit will be required to induce flow through the duct for engine running on the ground and in climbing flight. The passage areas are arranged so that the air velocity does not exceed 100 m.p.h.

Summarizing this section, it may be said that there is scope for improvement in installation technique for both the radial and in-line types of powerplant. In comparing nacelle forms on a surface area basis there is little to choose between them, but the in-line type has the advantage so far as duct entry and spoiling losses are concerned. On such installations as would permit of the engine being housed in the leading edge of the wing, however, the lighter radial engine will have the advantage.

(*c*) *Drag equivalent of powerplant weight.* – In a previous section of this paper I have endeavored to outline the main characteristics affecting engine weight and its effect upon simplicity, maintenance, and prime cost of the powerplant. Weight, however, must also be reviewed from the aerodynamic aspect as producing an additional drag equivalent of the complete powerplant.

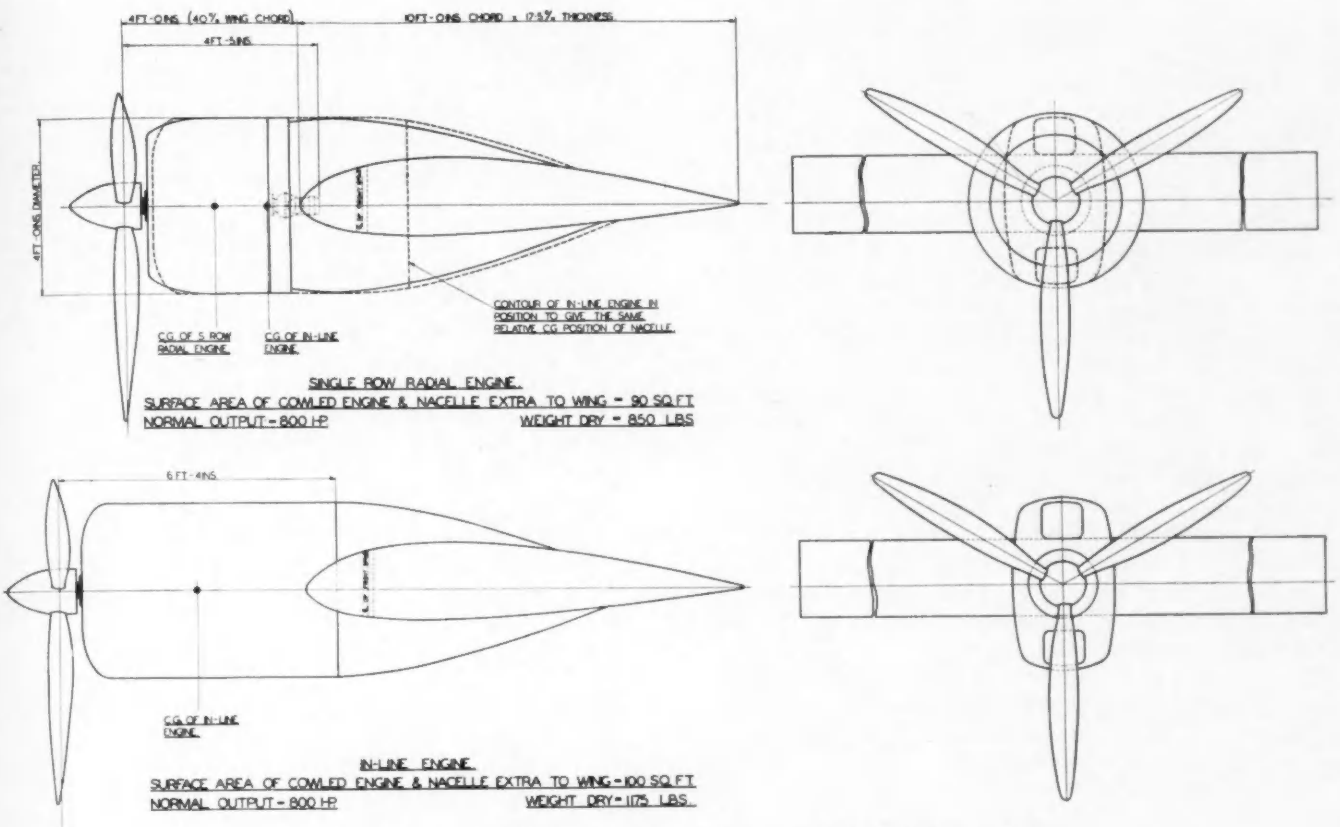


Fig. 17 – Comparative Nacelle Forms for In-Line and Radial-Type Engines

It has been pointed out under item (*b*) of this section that the relationship between the wing thickness and cowl diameter influences the nacelle drag and, with increased wing thickness, the rate of gain will favor the radial since the improvement is largely associated with the reduction of duct entry loss.

Probably with this point in mind, small-diameter double-row radial air-cooled engines recently have been developed for high-speed twin-engined military aircraft and were prominent features of the last Paris Salon. I have given some considerable thought to this development and have explored the merits of the two-row radial as compared with the single-bank in this category with regard to mechanical layout, weight, and cost.

Some few years ago when the results of the Schneider Trophy machines were fresh in our minds, there was a slogan – that reduction in drag equivalent to 1 lb. at 100 ft. per sec. would be equivalent to a permissible increase in weight of

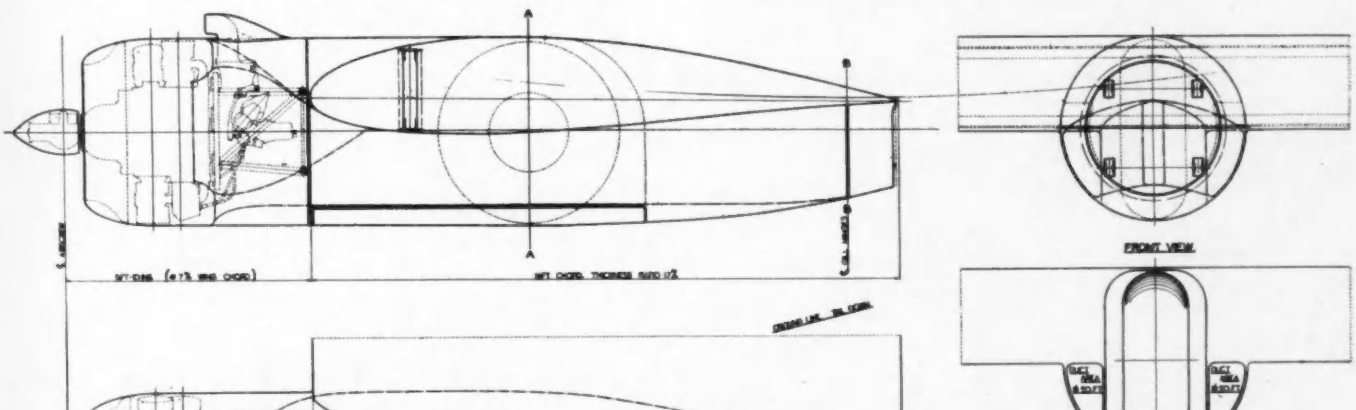


Fig. 18 – Double-Row Radial-Engine Nacelle Arranged for Controllable Ducted Cooling

100 lb. This statement is open to misinterpretation and, to arrive at a proper relationship, the weight factor must be considered as affecting wing surface drag, landing speed, and so on of the aircraft.

How important this weight factor is can best be illustrated, I think, by a definite example. Captain Barnwell, who is responsible for Bristol aircraft design, has examined the comparative performance of two twin-engined single-seater fighters, having double-bank and single-bank radial engines respectively and, for the purpose of comparison, the wing loading on the two aircraft is constant, so that the landing speeds are the same. The relevant figures of engines and aircraft are shown on Fig. 19, from which it will be seen that the top speeds of the two aircraft are approximately equal, the drag of the increased wing surface, due to the extra weight of the small double-row engine, offsetting the increased nacelle drag of the larger but lighter single-row type.

Fig. 20 shows a view of a scale model of these two engines mounted on the leading edge of a suitable wing.

By analogy I think that it would be fair to state that, on comparable aircraft designed around the radial and in-line engines, little advantage can be claimed by either in regard to the relative wetted surface and overall drag.

After examining further the various factors that affect engine layout from the aerodynamic standpoint and assessing the various drag figures as shown in Fig. 21, there does not appear to be any appreciable advantage with any one type so that the final verdict will have to be obtained from the consideration of other qualities, such as first cost, production in time of emergency, installation simplicity, easy maintenance and repair, and fuel consumption.

I think that low power-weight ratio will always be of fundamental importance, and it would appear that the only justification for departing from this characteristic would be

CASE I SINGLE ROW 9 CYLINDER ENGINE

CASE II DOUBLE ROW 14 CYLINDER ENGINE

ITEM	CASE I	CASE II
ENGINE DIAMETER	46·5"	40·0"
ENGINE POWER	750 HP	750 HP
ENGINE WEIGHTS (NETT DRY)	1640 lbs.	2000 lbs.
POWER PLANT ACCESSORIES :- AIRSCREWS, EXHAUST SYSTEMS CONTROLLABLE COWLS, ENGINE MOUNTINGS NACELLE STRUCTURE, STARTING GEAR, OIL COOLERS, FUEL & OIL SYSTEMS, ENGINE CONTROLS & INSTRUMENTS, INTAKES, FILTERS & PUMPS WITH DRIVES.	1450 lbs.	1450 lbs.
FUEL, OIL & TANKS ($1\frac{1}{4}$ HRS)	865 lbs	865 lbs
MILITARY LOAD	1150 lbs	1150 lbs
STRUCTURE WEIGHT	2183 lbs	2425 lbs
TOTAL WEIGHT	7315 lbs.	7890 lbs.
WING AREA	244 sq.ft.	263 sq.ft.
WING LOADING	30 lbs sq.ft.	30 lbs sq.ft.
POWER LOADING	9·75 lbs/HP	10·5 lbs./HP.
TOP SPEED	375 m.p.h.	376 m.p.h.

Fig. 19 – Effect of Powerplant Weight and Diameter – Comparative Performances of Twin-Engined Fighters

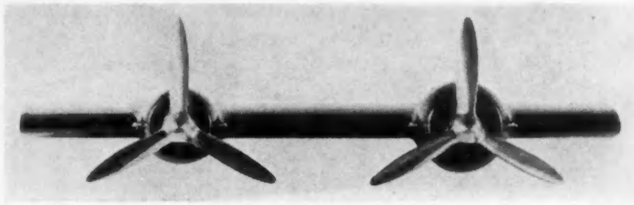


Fig. 20 – Scale Model of 750-Hp. Single- and Double-Bank Radial Engines Mounted on Wing

the introduction of specialized engines completely buried inside the wing.

Standardization of Complete Power Units

The standardization of all aircraft components is one of the most pressing needs of the industry today. Progress of

	RADIAL	IN LINE
MAXIMUM POWER (100 OCTANE)	800 HP.	800 HP.
WEIGHT - NETT DRY	850 LB.	1175 LB.
	DRAG AT 100 FT PER SEC.	
TOTAL INTERNAL COOLING DRAG.	1·5 LB	·5 LB.
NACELLE DRAG.	7 LB	7 LB.
DRAG, DUE TO DIFFERENCE IN POWER PLANT WEIGHT. (WING LOADING 25LB. SQ.FT.)	–	1 LB.
TOTAL	8·5 LB	8·5 LB.

Fig. 21 – Installation Drag of Radial and In-Line Air-Cooled Engines

aircraft design has not always assisted in this respect since it usually has been achieved in the past by change and fundamental difference of construction. Until comparatively recently the bulk of machines were of biplane form, and the location of powerplants varied with each individual design so that any question of a standard power unit was a practical impossibility. Fortunately, today progress has been achieved along lines which facilitate the adoption of this principle due to the localization of power units on monoplane wings.

The standardization and supply by engine constructors to aircraft manufacturers of complete power units ready to install in the aircraft as opposed to the supply of bare engines, is a broad subject almost worthy of a paper on its own. Nevertheless in this section a brief reference will be made to this important subject because so much interest is being taken in it at the present time, and because it is a matter which, it is envisaged, must be tackled and put upon a proper basis during the 5 years under review.

From the economic standpoint the saving in cost and time of the design staffs, together with the simplification of stores equipment, would be of considerable value to the Royal Air Force, aircraft constructors, and civil operating companies. An equally, or even more, important economy to be effected by the use of the standardized power unit as compared with the conventional installation is the saving in time during which an aircraft would be out of commission when it is necessary to change engines.

Air-cooled powerplants generally, and particularly air-cooled radial engines, are suited especially to this standardized unit construction, and it is suggested that it will be worth while reviewing this matter in order to see upon what lines standardization can be achieved most readily.

Some 14 years ago the Bristol Aeroplane Co. endeavored to introduce such a system and pioneered an engine unit on the

swinging-mounting principle, hinged at the bulkhead. This unit was tested out successfully on a number of machines and, although it achieved a measure of success, the scheme was before its time and did not receive serious support. Recently this matter has again come into prominence; the present trend in design readily lends itself to the principle of standardized power units for radial air-cooled engines.

In these installations, the exhaust system, removable cowling, and controllable gills, are standardized units, built into the aircraft by the aircraft constructor in collaboration with the engine maker. This development is only the commencement of what can be accomplished now that modern aircraft are stabilized into a more concrete series, and it is suggested that the scope should be extended considerably, the engine constructor providing a quickly removable engine mounting plate together with a standardized frame structure between it and the fireproof bulkhead; within this space a number of engine components should be installed in a manner best suited for their proper functioning, accessibility, and to facilitate easy power unit removal.

Considerable progress has been made along these lines in the U. S. A., and Fig. 22 shows views of the Pegasus-Douglas installation with standardized power-unit construction.

Top-left is an exterior view of the nacelle – top-right is a view of the nacelle with cowling removed, showing the grouping of pipe connections at the bulkhead – bottom-left is a rear view of the power unit on a sling ready for assembly, complete with cowling, exhaust, and oil systems – bottom-right is a view of the fireproof bulkhead showing four engine-mounting attachment points of the Lord flexible type, electrical plug connections, engine controls, and so on.

All multiengined aircraft will have their power eggs in nacelles mounted centrally or dropped relative to the wing according to design requirements.

It is appreciated that wing chords will vary with different designs and Fig. 23 shows a series of geometric arrangements that are possible on a radial installation with wing chords of 12 and 16 ft. The diagrams on the left illustrate dropped nacelles, and on the right, central nacelles, in each case with the propellers located at 30 per cent and 50 per cent of the chord ahead of the leading edge.

Installations employing conventional controllable gills should be arranged so that the gill exit has a reasonable clearance ahead of the leading edge. The engine could be located nearer to the wing when ducted installations are used and, although a standard mounting structure is not incompatible

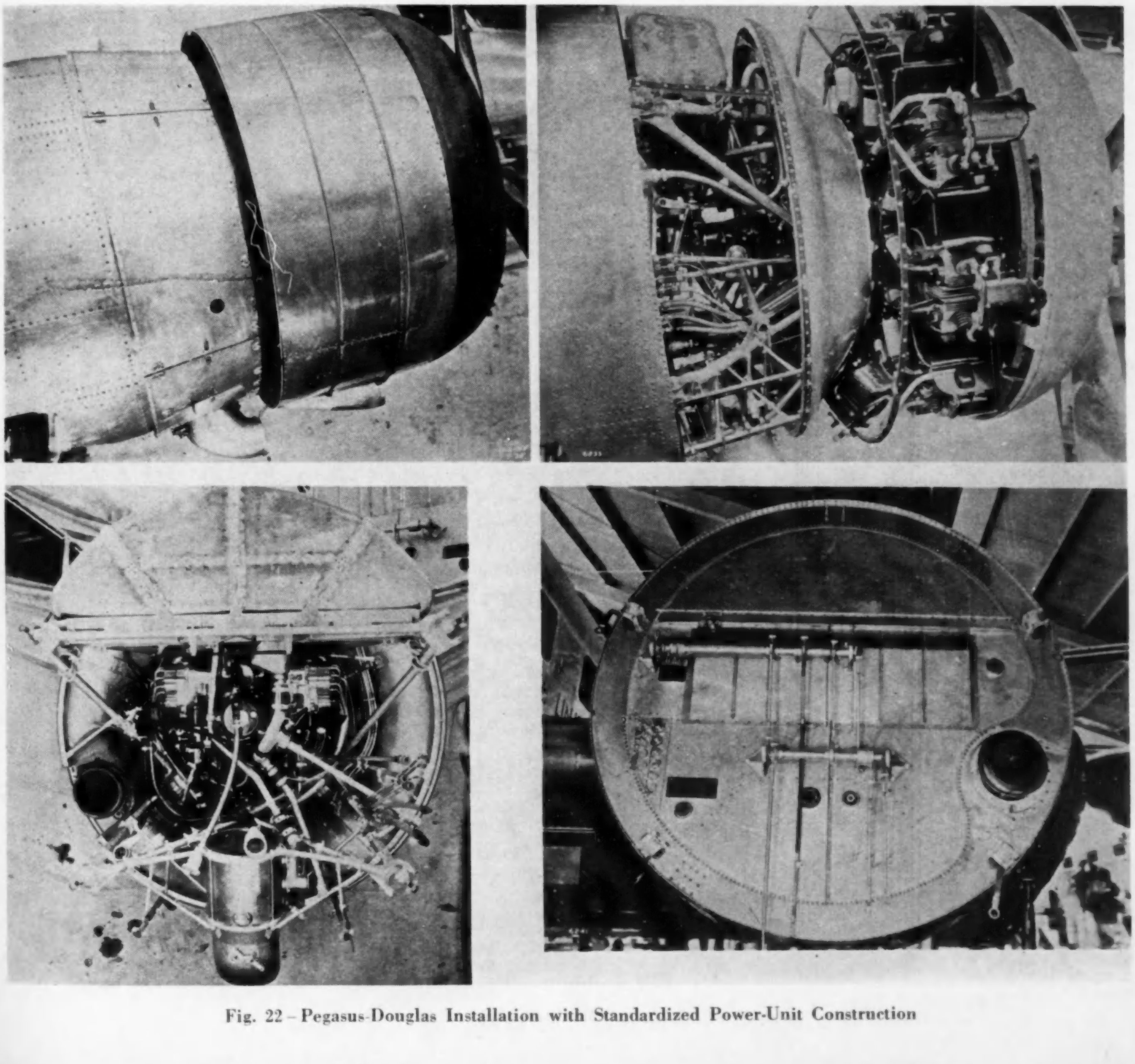


Fig. 22 – Pegasus-Douglas Installation with Standardized Power-Unit Construction

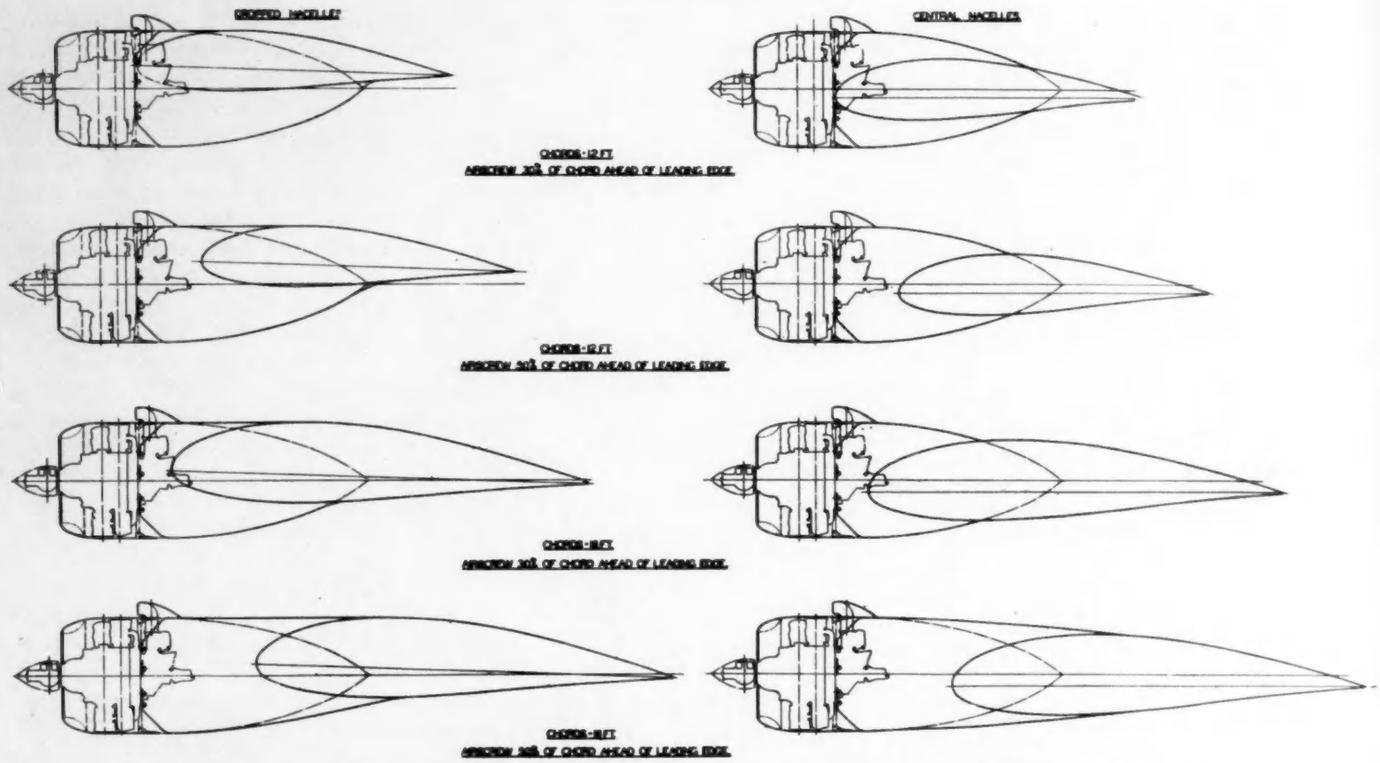


Fig. 23 – Possible Geometric Arrangements of Conventional Nacelles on Wing Chords of 12-16 Ft.

between the two systems, the latter might restrict the disposition of attachment points on the normal fireproof bulkhead line.

The principal dimensions and anchorage points must be common to all of these alternative arrangements, namely:

(1) The distance between the normal bulkhead and the engine.

(2) The four attachment points on the plane of the bulkhead.

The following design considerations will decide the position of these four points:

(a) Type of construction and form of the after body nacelle – monocoque or strut braced.

(b) Undercarriage and wheel housing.

(c) Oil tank and oil cooler installation.

(d) Provision of sufficient space for cooling air flow in the case of the completely ducted installation.

Fig. 24 shows diagrammatically two alternative cooling systems arranged for completely standardized power units, one by the conventional controllable gill, and the other by adjustable exit at the trailing edge, on the underside of the wing.

It is suggested that the engine mounting might consist of a triangulated tubular structure attached to four standardized and accurately jigged structural points on the bulkhead. These joints can be conveniently arranged for a ball-ended spherical housing.

The front end of this structure would be finished by four bolt-ended sockets to which a quickly detachable engine plate could be mounted. The engine would be attached to this plate in the normal manner, either rigidly or through suitable rubber mountings.

This apparent duplication would serve a dual purpose, in that the complete mounting with accessories could be standardized for production but, in certain cases, operators would have the option of detaching the engine complete with mounting plate if they did not wish to carry duplicate structures, oil tanks, and so on.

The complete unit should include provision for the following services and accessories, which can be divided into six groups:

Group I—An auxiliary which may be driven through the single drive remote gearbox.

(1) Electric generator.
(2) High-pressure air compressor.
(3) Low-pressure air compressor.
(4) High-pressure fluid pump.
(5) Vacuum pump.

Group II—Units which may be located on, and detached with, the engine mounting.

(6) Oil tank.
(7) Oil cooler.
(8) Oil cleaner.
(9) Starter magneto.
(10) Exhaust-gas analyzer.
(11) Fire-extinguishing system.

With this arrangement of engine and auxiliary units the number and type of connections which must be broken to permit removal of the power unit can also be divided into groups.

Group III—Electrical connections.

(12) Engine starter leads.
(13) Ignition leads.
(14) Thimble-couple leads.
(15) Oil-thermometer leads.
(16) Exhaust-gas-analyzer leads.

Group IV—Hydraulic or union connections.

(17) Gasoline feeds (to and from engine-driven pump).
(18) Oil-pressure gauge.
(19) Boost gauge.
(20) Fire-extinguishing system.

Group V—Mechanical connections.

(21) Carburetor hot-air-intake control.
(22) Carburetor slow-running cutout control.
(23) Oil-cooler air-intake control.
(24) Controllable-pitch propeller control.

Group VI—Other connections with alternative methods of operation.

(25) Throttle and mixture controls – mechanical or hydraulic.

(26) Tachometer – mechanical coupling or electrical.

(27) Variable-cowling gill control – mechanical or electrical.

The scope of this subject is too great to be reviewed fully in the space at my disposal, but the uniformity of the design of modern aircraft has brought us to a stage where the principles just enumerated must be considered seriously for each type of engine, and brought to a satisfactory conclusion.

It is appreciated that it is not likely that it will be possible to have only one standardized power unit for each type of engine, but it is hoped that it may be possible to limit the number to two.

Conclusions

Having briefly touched on what is believed to be the main factors governing the trend of air-cooled aero engines for the next five years and having suggested the four types of engine which I think will meet military and the larger civil transport requirements during this period, I will conclude by endeavoring to sum up the most promising layouts for these four sizes, in the hope that it may promote discussion and prove helpful to the air-cooled aero-engine designer in deciding which road he must pursue for the immediate future.

Earlier in this paper it has been suggested that the trend will be toward multiengined aircraft for all purposes, and these conclusions are based on this definite opinion.

Undoubtedly, as aircraft design and manufacturing technique advance, so the total drag of aircraft will approach more closely to the ideal as expounded by Prof. Melville Jones, namely – that due to turbulent skin friction. Will aeroplane designers eventually be satisfied to meet these conditions with the conventional powerplant as they know it today? It would appear to me that, to cope with this problem, the general trend will be to submerge power units entirely within the envelope of the wing if these ideal results are to be obtained.

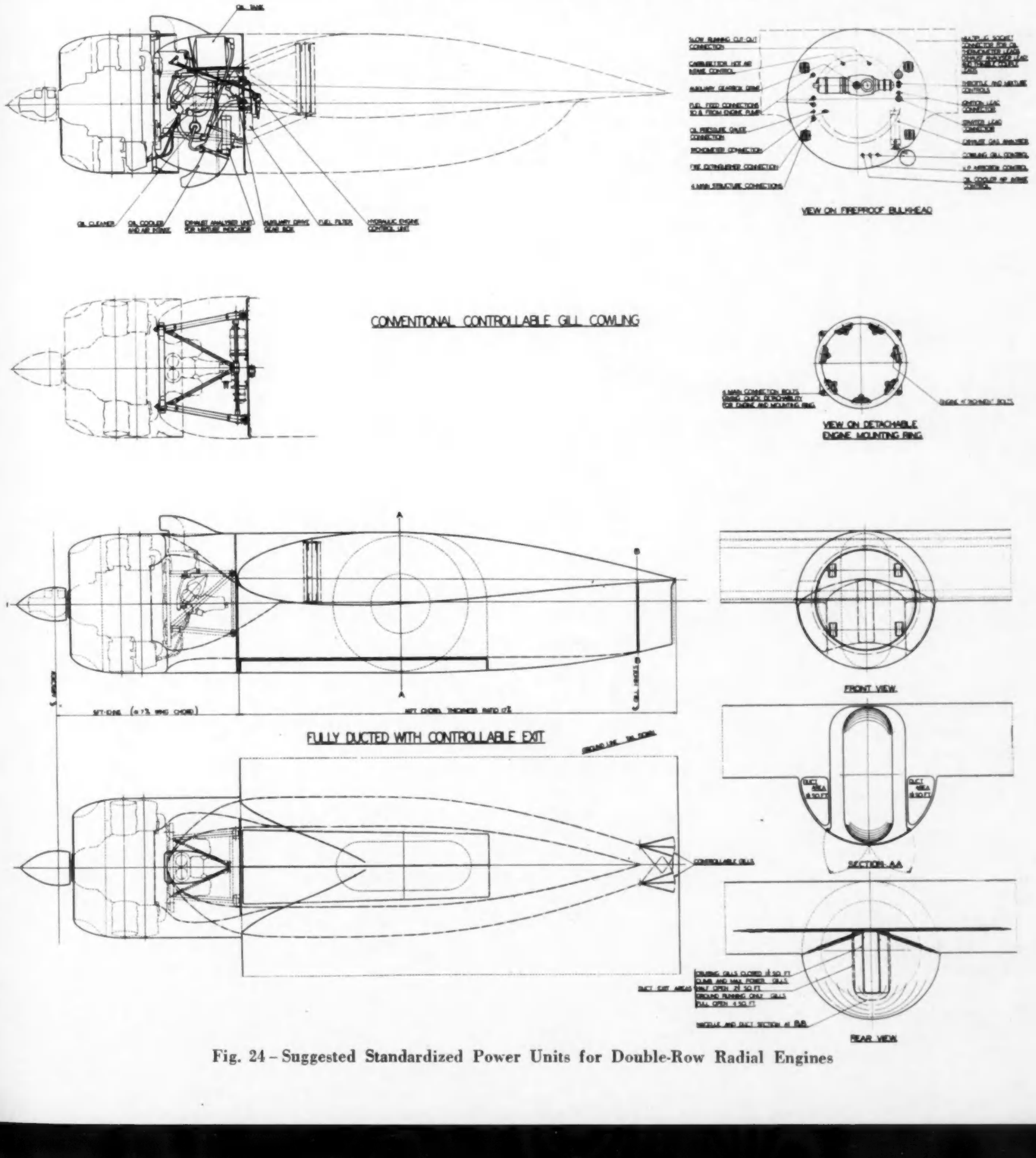


Fig. 24 – Suggested Standardized Power Units for Double-Row Radial Engines

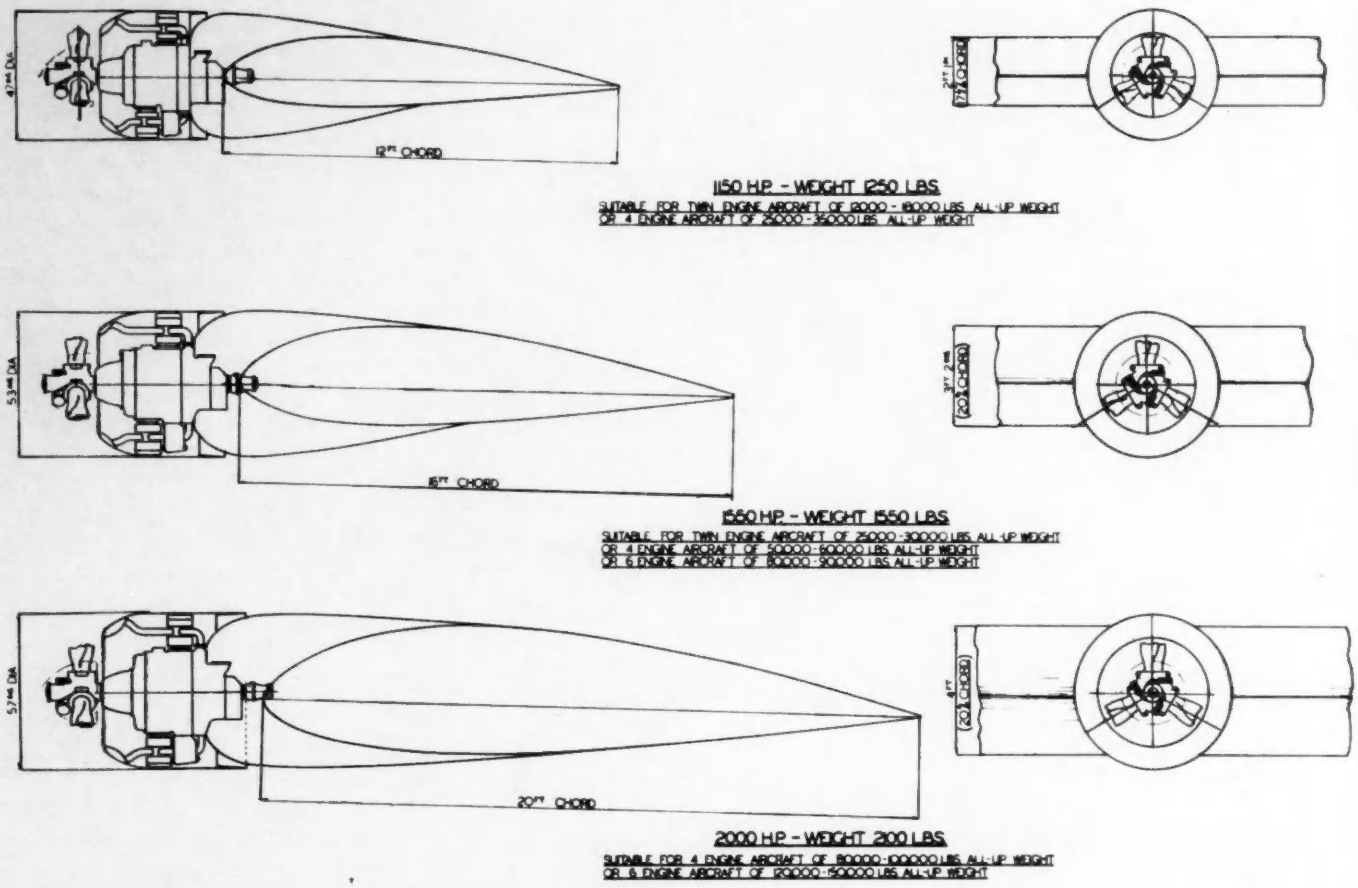


Fig. 25 – Comparison of Wing-Mounted Double-Bank Radial Engines

Can such fundamental changes in the layout of the four suggested sizes of powerplant be envisaged in five years and are they necessary in all four categories? Can the difficulties outlined in this paper be overcome, as well as the many problems affecting the aircraft which would be necessary with such a drastic change of powerplant layout?

I would suggest that a complete changeover of all four categories of engines is out of the question in the period under review, and will most probably never be required since, in the larger classes where four or more engines will be standardized on one aircraft, the wing thickness will be such as to permit of the radial engines being housed inside the leading edge. Quite apart from the engine designers' problems, there are so many basic aircraft ones to settle also which become increasingly difficult, the greater the number of engines employed.

Full-scale research work must be undertaken in regard to the position of propellers on the leading edge of the wing, the effect on the wing and spar designs of accommodating the engines accessibly, dealing with the stowage of undercarriages, and a host of other fundamental problems.

I suggest that drastic changes of this sort must come into being, and be investigated on one type first, as we have seen in the case of the classic Douglas series, and the placing of the engine inside the envelope will, in my opinion, first come into being in the smallest category.

My interpretation of the four sizes of engines, during the period under review, would, therefore, be as follows:

(1) The first category – 750 hp. for 820 lb. weight is suitable for twin-engined civil and military aircraft. I would suggest that this size of engine is suitable for twin-engined destroyer or multiplace fighter types and, in the period under review, I think there is justification for serious consideration of the flat engine entirely buried in the envelope of the wing for these types of aircraft. Some 18 months ago, the Bristol Aeroplane Co. produced a layout for such an engine, but urgency of other work and the need for an entirely new technique of aircraft design prevented it from receiving very serious consideration. Provided a sufficiently bold and specialized step can be justified for military purposes for the highest speeds, it is believed that this is the ideal solution for the future for the smallest category of engine and, apart from the fact that the engine drag approaches the ideal solution, an aircraft so equipped has many other advantages.

It is suggested that the radial engine is the ideal form in this category for more general purpose and civil types.

It would appear, therefore, that two types of engine will have to be envisaged for this category – the radial engine in compact form, and the specialized flat engine. Sacrifices in regard to weight, cost, simplicity, and so on, will all have to be made on account of the flat engine, and many problems in regard to installation investigated carefully.

(2) For the other three categories of engines, namely: 1150 hp. for 1250 lb., 1550 hp. for 1550 lb., and 2000 hp. for 2100 lb., it is firmly believed that the radial engine will hold its own during the period under review. For the sizes and speeds of aircraft envisaged for which these engines are intended, it is submitted that the Royal Aircraft Establishment, and other authorities, have demonstrated that it will be possible to achieve even lower drag installations than at present in vogue, by retracting the radial type of engine toward the leading edge of the wing, in conjunction with duct cooling. Fig. 25 shows, in sectional form, conventional double-row radial engines to meet the last three categories of powerplant.

I am somewhat diffident about expressing any opinion on the section of the wings under consideration and expect

(*Continued on page* 467)

Aircraft Powerplant Trends

By George J. Mead
Vice-President and Chief Engineer, United Aircraft Corp.

THE rapid increase in the size of our air transports, as well as the requirements for higher cruising speeds, forewarn of the need of powerplants of decidedly greater power. The further development of the existing standard types may be relied upon to ultimately provide at least 50 per cent greater output. There is, however, definite evidence now of the need of engines of even greater power in the period immediately ahead, which need has focused attention on other types in which additional displacement may be provided through the employment of a greater number of cylinders.

Studies indicate that there is an opportunity of reducing the powerplant drag sufficiently to effect a saving in fuel at least as great as is promised by further improvement in specific consumption. For this reason the form and location of the new powerplants, as well as the method chosen for cooling them, will be dictated largely by the resulting effect on operating costs. It seems likely that two new engine types will result in which twice as many cylinders may be employed as is now common practice and proportionately greater power will be provided.

The problems involved are decidedly more complex than hitherto have been encountered, but the industry is now equipped with both personnel and experience to deal effectively with them. For this reason, there is little question that powerplant development will keep pace with the requirements.

TRANSPORT aviation is expanding rapidly in America both because of improved business conditions and the excellent record of the transport companies. The new airplanes being laid down, both land transports and boats, on the average, are twice the size of their immediate predecessors measured in terms of gross weight. Never before in the history of our industry has there been such a large increase in size in such a short period. See Fig. 1. Coupled with the demand for larger airplanes is the requirement for decidedly higher cruising speeds. To meet these demands the total thrust horsepower per airplane is being increased materially. Operating costs are becoming more and more important due to the competition among airlines, as well as between them and other forms of transportation. The engineer consequently is forced to give serious consideration to utilizing the power available in the most efficient manner, as well as to reducing maintenance costs. The maximum dependability also is demanded, to insure safety as well as to maintain the predetermined schedules. The new airplanes, therefore, are designed to give efficient performance at take-off and under cruising conditions rather than, as heretofore, at their top speeds. This practice provides for carrying the revenue-producing load at the minimum cost per ton-mile.

With the trend toward larger airplanes and higher speeds, the question naturally arises as to whether the engine develop-

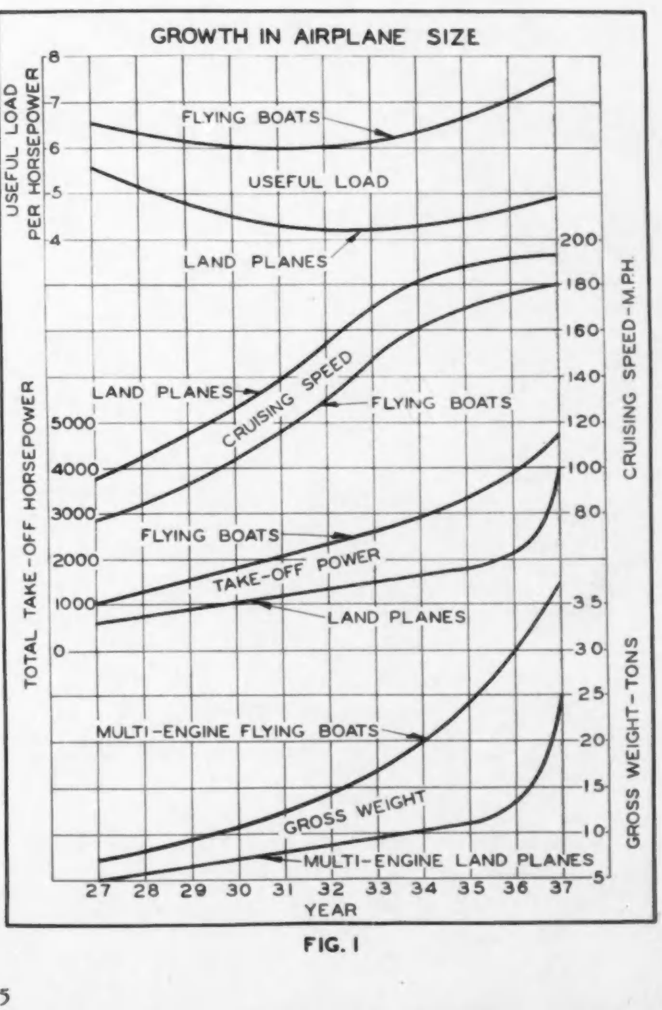


FIG. 1

[This paper was presented at the Semi-Annual Meeting of the Society, White Sulphur Springs, West Va., May 4, 1937, by courtesy of the Royal Aeronautical Society; the paper was prepared for presentation at the Meeting of the Royal Aeronautical Society, London, England, April 22, 1937.]

ment can keep pace with the requirements. It is my object, therefore, to forecast the probable development of the orthodox type of four-stroke internal-combustion engine using gasoline. To make this forecast, it is desirable first to examine the trend of the last decade as being the best indication we now have of probable future developments. The output per liter has risen steadily from 18 to 35 hp., as shown on Fig. 2, and the crank speeds have increased from 1900 to 2800 r.p.m., or roughly 50 per cent. During the same period the take-off mean effective pressure has been increased from 124 lb. per sq. in. to nearly 170 lb. per sq. in., and the cruising pressures from 90 to 135 lb., while the operating periods between overhauls have increased from 300 to 600 hr.[1] Can this rate of progress be expected in the future, or may it be improved? Research authorities on both sides of the ocean have already reported outputs of 100 hp. per liter. To be sure, these experimental engines would hardly measure up to the requirements of commercial operation and, besides, they require special fuels. Nevertheless, this value gives an objective to be attained ultimately by our standard engines. It is interesting to note, in this connection, that we are fast approaching the goal of 40 hp. per liter set up by Mr. Fedden in his paper[2] before the Society in December, 1933.

The standard engine types in our commercial service today

[1] Since this paper was presented, a new engine has been announced by Pratt & Whitney with an output of 40 hp. per liter and a take-off m.e.p. of 204 lb. per sq. in.

[2] See *The Journal of the Royal Aeronautical Society*, March, 1934, pp. 169-235; "Possible Future Developments of Air-Cooled Aero Engines," by A. H. R. Fedden.

[3] See S.A.E. Transactions, September, 1937, pp. 415-420; "Value of Octane Numbers in Flying," by D. P. Barnard; April, 1931, pp. 531-541; "Increasing the Thrust Horsepower from Radial Air-cooled Engines," by Philip B. Taylor; and May, 1936, pp. 161-175; "Rating Aviation Fuels – in Full-Scale Aircraft Engines," by C. B. Veal.

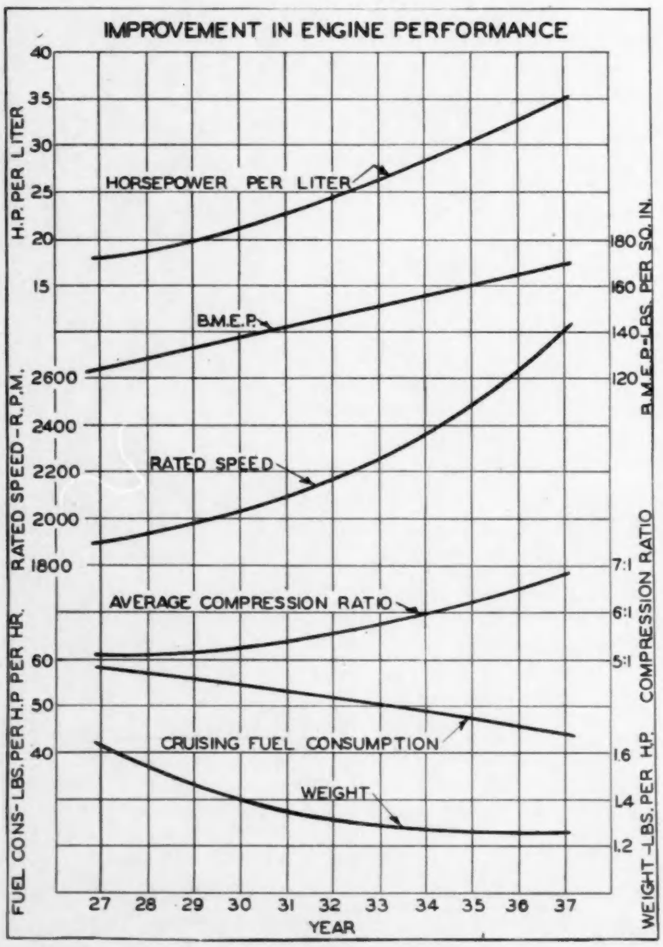
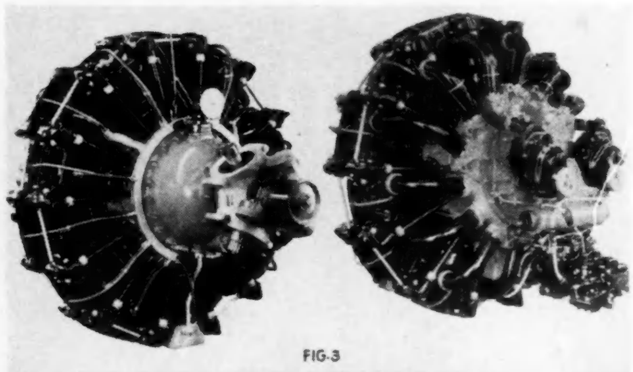


FIG.2



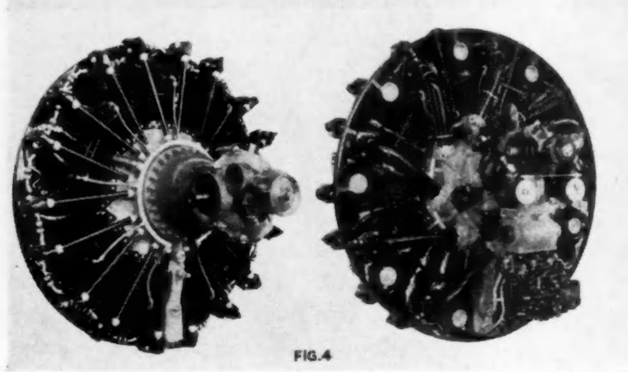


Fig. 3 – Twin Wasp Fourteen-Cylinder Engine

Fig. 4 – Hornet Nine-Cylinder Engine

are single- and two-row air-cooled engines of nine and fourteen cylinders respectively. See Figs. 3 and 4. The new airplanes now being built require take-off powers of 1100 to 1200 hp. and continuous cruising powers of 650 to 750 hp.; fuel consumptions of 0.42 to 0.44 lb. per hp-hr. are being guaranteed. The engines are geared and supercharged and weigh with this equipment, ready to run, from 1.2 to 1.3 lb. per take-off hp. The vee-type twelve-cylinder liquid-cooled engine, although standard elsewhere, is very little used in transport service in the United States.

Improvement of Existing Types

The need for greater power naturally directs attention first to the opportunities for improving the performance of the present standard types. Such improvement may be provided through the use of fuels with higher knock rating, additional displacement, better cooling, greater boost, higher operating speeds, and lower fuel consumptions.

Fuels

The improvement in fuels has without doubt been the greatest single aid in bettering engine performance during the past ten years. The general effect of this improvement on output is shown on Fig. 5. Unfortunately, authorities are not yet in agreement as to the precise effect of better fuels on engine performance. For this reason three curves[3] are given, and it is to be presumed that the final evaluation is likely to be a mean of these extremes, especially as all three curves pass through the same end-points. Despite the increase in cost, our airlines have standardized pretty generally on 87-octane fuel. Actual experience has shown that the better grades of gasoline not only give superior performance, but reduce the maintenance cost to such an extent as to more than justify the higher fuel cost. During the latter part of 1936, several of our transcontinental lines commenced using 100-octane fuel for take-off because of the much greater payloads that could

thus be carried. Several excellent papers have been published recently both in England and in the United States analyzing the return in money value from the use of higher-octane fuels, and the general adoption of 100-octane fuel can be predicted safely.[4]

Fuel experts seem generally of the opinion that further fuel development is entirely possible, but are far from unanimous on the probable course that this development will take. Most of the more common petroleum derivatives already have been investigated, and exploration of the less familiar hydrocarbon groups is under way. At the same time a new measuring stick is needed as the octane scale ends at 100. A different system for the measurement of the knock rating is also required, since the bouncing-pin system has been found wanting in the case of the higher-octane ratings. Another method has been devised by the U. S. Army Air Corps in which temperatures are substituted for pressures. This method apparently gives satisfactory results, at least to the end of the octane scale. Fuels of antiknock value well above 100-octane rating have been produced for laboratory experimental tests. Despite the importance of continuing the development of fuels with higher antiknock ratings, there appears to be another line of attack, as special fuels have been produced for racing engines of approximately 300 lb. per sq. in. m.e.p.

[4] See *The Journal of the Royal Aeronautical Society*, April, 1934, pp. 309-372; "Ethyl," and lecture delivered before The Royal Aeronautical Society, Jan. 8, 1937; "Fuels and Modern Aero Motor Design," both by F. R. Banks; see also *Aircraft Engineering*, January, 1937, pp. 13-18; "High Octane Fuels," by E. L. Bass; see also *Shell Aviation News*, December, 1936; "Influence of Fuel Properties on Air Line Operating Costs," by E. L. Bass and S. A. W. Thomson; see also *Journal of the Aeronautical Sciences*, March, 1935; "Aircraft-Engine Performance with 100-Octane Fuel," by Capt. F. D. Klein; see also S.A.E. TRANSACTIONS, August, 1936, pp. 304-312; "Future Possibilities of 100-Octane Aircraft-Engine Fuel," by Capt. F. D. Klein; see also S.A.E. TRANSACTIONS, September, 1937, pp. 415-420; "Value of Octane Numbers in Flying," by D. P. Barnard.

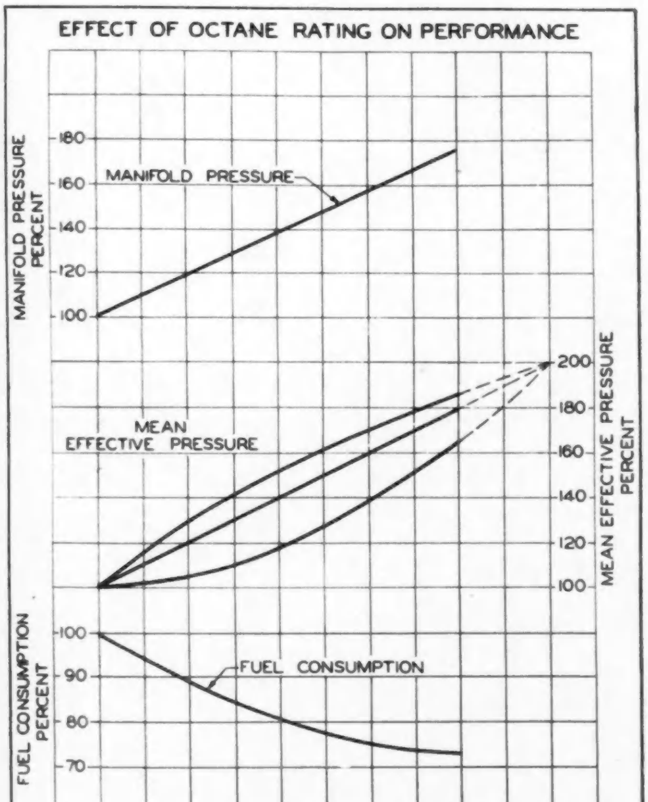


FIG. 5

and for experimental cylinders of over 500 lb. per sq. in. m.e.p. which did not have particularly high octane ratings. Undoubtedly the cost of these fuels is at present prohibitive, but it seems probable that the cost might be reduced or else some other fuels developed which will give equally satisfactory results at commercial prices.

Displacement

The trend in the development of existing types is toward the use of smaller cylinders and higher operating speeds. Maximum performance is actually being secured with the total displacement reduced from 10 to 15 per cent in the latest examples of nine-cylinder radial and twelve-cylinder vee engines. The smaller cylinders also permit the reduction of engine diameter or cross-section.

The exception to the general trend is the two-row radial. Here it may be feasible to use eighteen instead of fourteen cylinders, providing a satisfactory built-up crankshaft can be developed. This design would provide an increase in displacement of 25 per cent and correspondingly greater power. The diameter of such a combination will only be slightly greater than the fourteen-cylinder type with the same size of cylinders, as will be seen from Fig. 22.

Cooling

The maintenance of permissible operating temperatures of the parts exposed to the combustion space is one of the most serious problems of the designer today, for these temperatures determine the detonating characteristics of a cylinder on a given fuel and thus influence the rating of the engine. The usual effect of continuous detonation is cracked or scored pistons or cylinders and, therefore, is to be avoided.

To gain a better idea of the cooling problems involved, I propose first to review the progress to date before attempting to discuss possible improvements. The cooling of the exterior of the combustion-chamber is accomplished by the slipstream, either directly for the air-cooled or indirectly for the liquid-cooled engine. The direct method has much to recommend it and to date has been the simpler and lighter system. As a matter of fact, its weight saving brought it into universal transport use in the United States. The original wide-fin spacing with relatively small fin area, as shown at the left on Fig. 6, was sufficient for outputs of 18 hp. per liter, whereas the drag of the uncowled engine compared favorably with that of the water-cooled engine and nose radiator. The development of the low-drag cowl made the drag of the air-cooled engine comparable to that of the high-temperature liquid-cooled engine and external tunnel radiator. As power increased, corresponding additions were made in radiation surface, by reducing the pitch of the fins and increasing their length as shown at the right in Fig. 6. The latest improvement has been to direct and control the cooling-air flow by means of close or pressure baffles around the cylinders and adjustable trailing-edge flaps on the cowl, as shown on Fig. 7. This gradual evolution of the direct system has so far kept pace with the demand. However, it is no longer feasible to increase the fin area materially so that further improvement must come from increasing the mass flow of air over the cylinders. There is every indication that blower-cooling, as this might be termed, will permit carrying the power of air-cooled engines considerably higher.

Fundamentally, heat dissipation may be improved by increasing the mass flow of either the air or liquid over the combustion-chamber. For maximum output and minimum consumption, it is essential to maintain uniform temperatures over all of the combustion-chamber and that portion of the cylinder traversed by the piston. As it is perhaps easier to

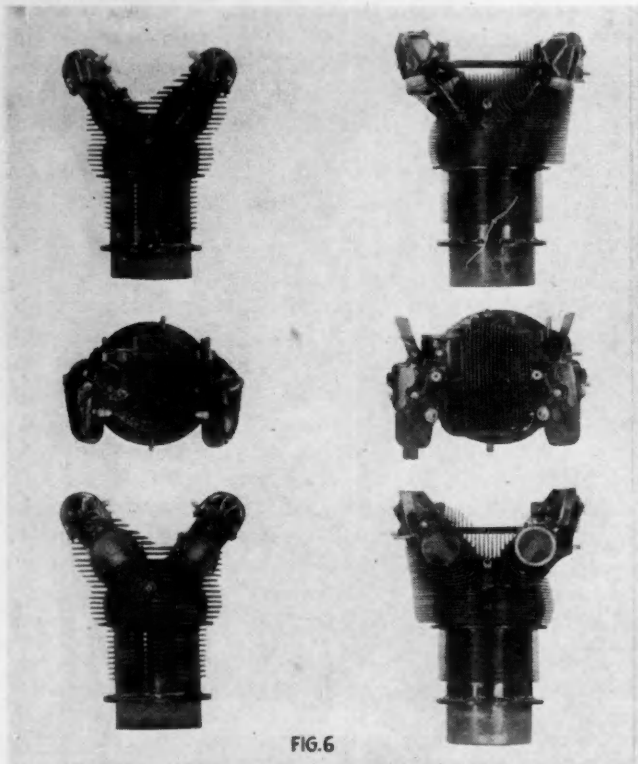


FIG.6

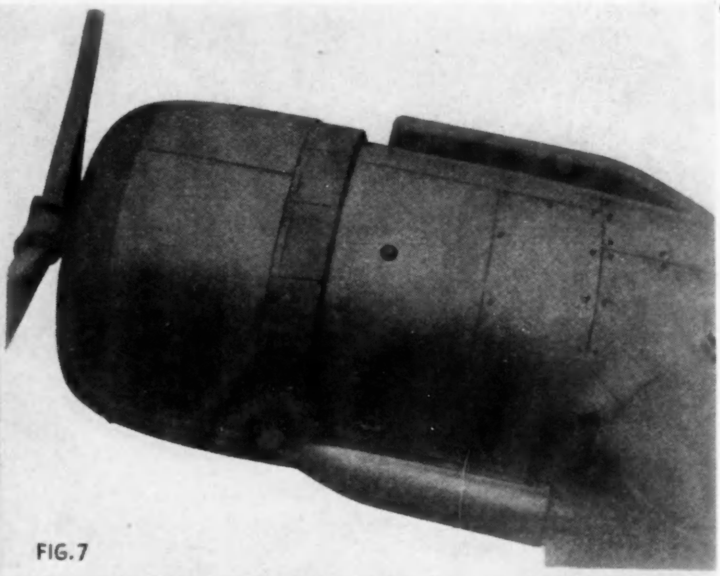


FIG.7

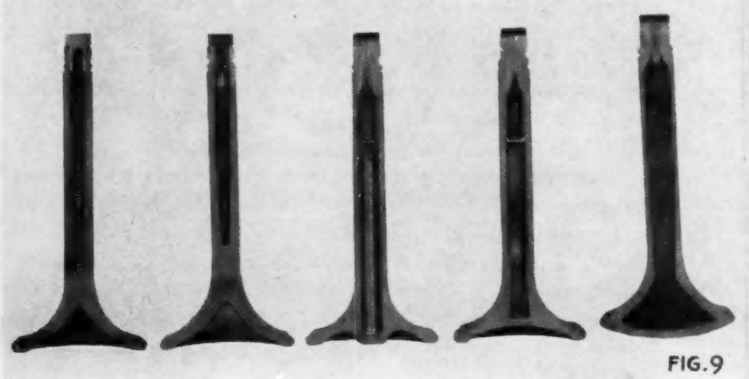


FIG.9

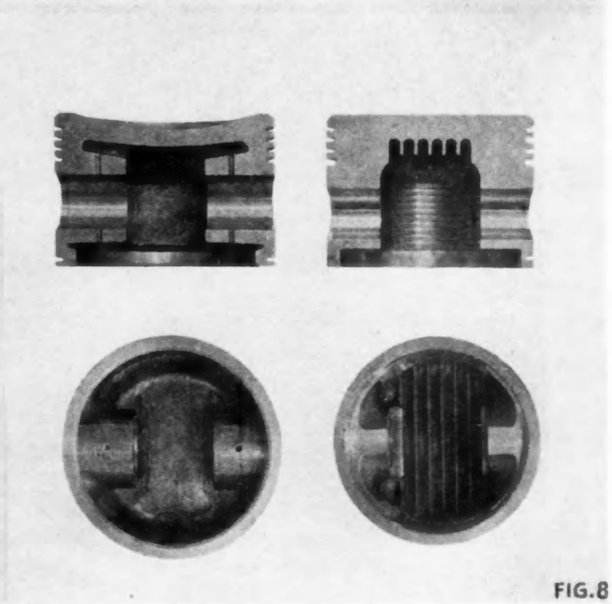


FIG.8

Fig. 6 – Comparison of Cooling Fins
Fig. 9 – Exhaust-Valve Evolution

Fig. 7 – Engine Cowl Flaps
Fig. 8 – Piston Evolution

meet this requirement with liquid than with air, this consideration may be a deciding factor. The air-cooled cylinder has the advantage of greater temperature difference between coolant and cylinder, but correspondingly profits less from the reduced atmospheric temperature at altitude. Further improvement in liquid-cooling centers on the elimination of thermal stresses in the cylinders and on better provision for heat transfer from the exterior surface of the combustion-chamber to the cooling medium. A great deal can be accomplished along these lines by applying the lessons already learned from air-cooling.

Only approximately 50 per cent of the combustion-chamber can be cooled by the cooling medium flowing over it. The opposite table shows a percentage analysis of a 5½- x 5½-in. cylinder with both two and four poppet valves and with a sleeve valve. A compression ratio of 7:1 is assumed, and two 18-mm. spark-plugs.

As will be seen from this table, the piston head is the largest area in the combustion-chamber which is not cooled by the slipstream. A large part of its heat dissipation is through the piston-rings to the cylinder barrel. For this reason, the number of rings has increased as power and temperature have been raised. The balance of the piston cooling is accomplished

Distribution of Interior Combustion-Chamber Area (5½- x 5½-in. Cylinder)

	Two Valves-Spherical Head	Four Valves-Roof Head	Sleeve Valve
Piston	44.0	40.5	35.5
Valves	13.3	11.8	25.8*
Spark-plugs	1.3	1.2	1.1
Remainder of combustion-chamber	41.4	46.5	37.6
Total	100.0 per cent	100.0 per cent	100.0 per cent
Total of heat-exposed area	100 per cent	107 per cent	116 per cent

*Exposed portion of sleeve with piston at top-center.

principally by oil thrown off the cranks. Fins were first added to the underside of the piston heads and then to the piston skirts to improve this cooling, as shown on Fig. 8. It is this heat flow to the lubricating oil which accounts for the steady increase in size of oil coolers.

The valves also account for a considerable portion of the combustion-chamber area. Since the inlet valves are cooled by the incoming mixture, the uncooled valve area is approximately one-half that shown in the table. The introduction of the hollow chemically-cooled exhaust valve has been the greatest single improvement in valve-cooling. Originally only the stem was cooled, but now a forging technique has been developed which permits making the entire valve head hollow. This construction is illustrated in the evolution of our exhaust valves as shown on Fig. 9.

The problem of spark-plug cooling is becoming serious and is made more so by the necessity for using shielding for proper radio communication. Some improvement has been obtained by reducing the plug size. The length of the threaded portion of the plug in the cylinder has been increased along with the reduction in diameter. This design has definitely reduced the plug temperatures, and a still further improvement has been made by locating the electrodes in a pocket rather than in the combustion-chamber itself. There is the further difficulty that plugs that operate satisfactorily at high output are likely to foul with oil when idling. All in all, we appear to be fast reaching a limit, and a more positive means must soon be provided to cool the spark-plug.

Superchargers

Superchargers, when first introduced, were used solely to restore sea-level power at altitude, as the fuels then available would permit little or no ground boost. Pressure-supercharging has now become necessary to increase take-off power, as well as for altitude operation. The present commercial practice is to use an engine-driven centrifugal supercharger placed between the carburetor and the cylinders. This location has been dictated principally through considerations of mixture distribution in the radial type engine, although it has the additional advantages of compactness and simplicity of drive. With such a system, the use of an intercooler is practically prohibited. The amount of boost is limited, in the absence of an intercooler, by the temperature of the mixture which, in turn, is a function of the peripheral speed of the impeller. Two-speed drives have been employed to reduce the impeller tip speed near the ground where the air temperature is higher. Unfortunately, in this type, the improvement in performance at the lowest and highest altitudes is more than offset by the reduction in performance at the intermediate altitudes where most commercial operations are carried out and, in particular, where excess emergency and take-off powers are required. Fig. 10 illustrates the normal and available powers of engines equipped with single-stage superchargers with both single- and two-speed impeller drives. Cruising powers are, of course, available to much higher altitudes than those shown for normal powers, but here again the two speed arrangement is somewhat at a disadvantage, as the fuel consumptions are greater at those altitudes where it is necessary to use the higher gear ratio.

There is little hope of further improvement in single-stage supercharging without the use of an intercooler. The practical way to employ one on a radial engine with carburetor is to use a two-stage supercharger and place the intercooler between the stages. Such a system provides for the decided

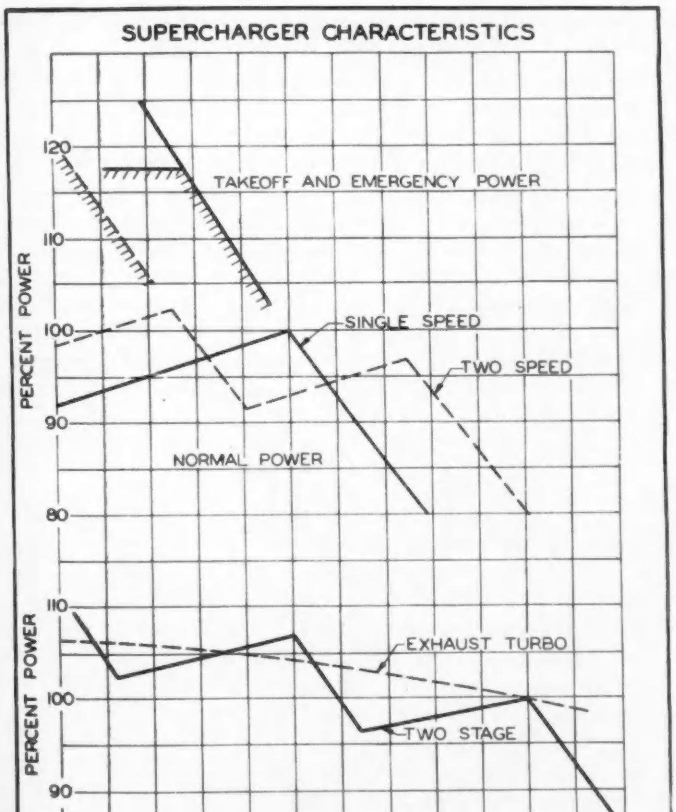


FIG.10

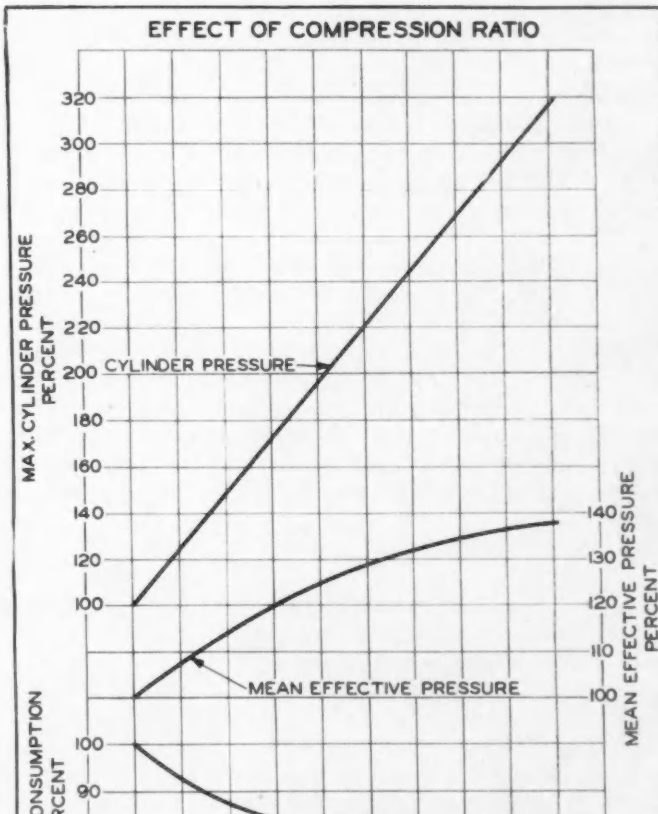


FIG.11

increase in boost which will be required if transport operations are to be carried to materially higher altitudes. Where the supercharger is not required for distribution, as in some types of in-line engines, the cooler may be placed between the supercharger and the carburetor by locating the supercharger ahead of the carburetor.

The ideal system for any engine type would be one in which the amount of supercharging could be regulated to fit each operating condition and altitude. This system requires that an infinite number of impeller speeds be available for a fixed impeller and diffuser combination. Furthermore, it should be possible to use an intercooler without interfering with distribution. The exhaust-driven turbo supercharger, when used with suitable distribution or direct fuel injection, essentially meets these requirements and may, therefore, become attractive for commercial use. It has the added advantage of reducing exhaust noise.

High-altitude transport operation will require the use of either an engine-driven two-stage or an exhaust-driven turbine. Consequently, a comparison of these two systems is of interest. Comparative curves are given on Fig. 10, assuming cruising operation at 25,000 ft. Both arrangements provide surplus power for take-off and emergency use beyond that which can be utilized safely in continuous service. Little or no experience has been had with either system in commercial operation as yet, so that it is difficult to evaluate the eventual trend. Generally speaking, the turbine may be preferred because of its flexibility and absence of restriction on the critical altitude.

Speed of Operation

Operating speed is limited both by the valve gear and by the crankpin loading. Continued refinement of the poppet-valve mechanism has thus far enabled it to keep pace with the requirements. One of our two-row engines with 5½-in. bore is rated at 2700 r.p.m. for take-off, which is illustrative of what may be accomplished with two valves per cylinder when operated by push-rods. The type of gear in which the cams operate directly on the valves is the best for maximum speed. It is, however, more applicable to the in-line engine than to the radial. On the whole, there seems little opportunity of much further increase in poppet-valve speeds for a given valve size.

The connecting-rod bearing loads, especially in the radial type of engine, are becoming a limiting factor. These loads increase directly as the mass of the rotating portion of the connecting-rod system and as the square of the speed. Practically no reduction in loading can be made by increasing the bearing areas beyond a certain point, as the added rod weight nullifies the possible gain. Further improvement must be made, therefore, by reducing the weight of the connecting-rod system and through better types of bearings and bearing alloys.

Specific Fuel Consumption

Specific fuel consumptions of 0.46 lb. per b.hp-hr. are being maintained by our single-row engines in transcontinental service. These engines are being operated at an average of 75 per cent of rated power, with 80-octane fuel and 6:1 compression ratio. The two-rows on the transpacific run are averaging 0.44 lb. per b.hp-hr. at a somewhat lower percentage of their rated power with 87-octane fuel and 6.5:1 compression ratios. Both the transcontinental and transpacific engines are equipped with automatic mixture controls. As far as I am aware, these figures are as good as have yet been achieved in transport service with either air- or liquid-cooled engines.

Continuous operation at the minimum consumption involves serious cooling problems for the engine designer. Exhaust-valve, spark-plug, and piston-head temperatures become critical under these conditions, and piston erosion is likely to be encountered. It is for this reason that the extremely low specific consumptions which can be demonstrated on the dynamometer are not yet necessarily feasible in commercial operation. The cooling problem now is actually more acute at cruising powers with low fuel consumption than at take-off or in climb.

As is well known, figures on specific consumption obtained in flight are subject to considerable error. This error is primarily due to the lack of accurate information on the power being developed. It has been customary to estimate the power from the manifold pressures; this is unfortunately an uncertain method. The need for an accurate method led to the development by Pratt & Whitney of its new torque meter. In principle, this meter consists of a hydraulic means of measuring the torque reaction on the fixed gear of the propeller reduction. With this device, power readings are precise within 1 per cent.

The most promising methods of obtaining lower fuel consumptions are through refinement in combustion-chamber design and the use of higher compression ratios. The research in connection with measuring the knock value of fuels has shown the decided effect of combustion-chamber form and construction on both the detonating and fuel-consumption characteristics of a cylinder. Turbulence and spark-plug position, as well as uniform distribution, are undoubtedly other factors influencing minimum consumption.

Compression Ratio

The improvement in performance due to higher compression ratios is shown by Fig. 11. The progress in this direction has been slow because of the detonating limitations of fuels and the destructive effects of the accompanying higher explosion pressures. Ratios at least up to 9:1 afford material reductions in consumption, after which the improvement commences to taper off. In the United States, ratios of 6½ to 7:1 are now standard for 87-octane fuel. Presumably, the use of 100-octane fuel will ultimately permit the use of ratios of 7½ to 8:1 with a corresponding reduction in fuel consumption. The sleeve valve eventually may be capable of even lower consumptions, as it is generally conceded that it enables the use of one integer of compression ratio higher than can be used by a poppet valve operating on the same fuel. An incidental advantage of the higher ratios is the improvement in power of approximately 5 per cent for each added integer of compression ratio. However, if increased power alone were required, it would be better to secure it with boost, since the maximum pressure would be lower.

Distribution

The equal distribution of the charge to the various cylinders has a definite bearing on fuel consumption as the leanest cylinder limits the performance of the entire engine. Supercharging has generally improved distribution because of its effect on the temperature of the charge although, in the radial engine, there has been a further improvement due to the symmetrical nature of the intake system, which is centered on the impeller. This arrangement no doubt partly accounts for the excellent consumptions referred to in connection with our radial engines. Direct fuel injection holds promise of a possible further improvement in this direction.

Minimum fuel consumption cannot be maintained in service by manual adjustment of the mixture-control due to the need for frequent resetting and, because it is as yet impossible to determine accurately the engine-operation conditions. The exhaust-gas analyzer is not, therefore, a particularly helpful

solution for the commercial pilot since it still leaves the actual setting of the mixture controls to him. To meet this requirement Pratt & Whitney has developed an automatic mixture control,[5] and indications are that similar equipment will be required on all future engines where continuous economical operation is desired.

The use of the constant-speed propeller makes possible the operation of the engine at the most advantageous combination of speed and mean effective pressure for minimum fuel consumption. We have found that the best results are obtained by keeping the mean effective pressure reasonably high and lowering the speed since this method, in effect, improves the mechanical efficiency. This condition is illustrated graphically by Fig. 12.

Sleeve Valve

Mention should be made of the single sleeve valve as a possible improvement of existing types. Its principal advantage lies in reducing the maximum combustion-chamber temperature through elimination of the exhaust valve. As already mentioned, this design permits the use of approximately one integer more of compression ratio with a given fuel, which results in improving the output and the fuel consumption as shown by Fig. 11. It is doubtful whether the sleeve valve gives materially better volumetric efficiency than can be obtained with poppet valves due to the limitations of sleeve travel and the flow characteristics of the ports. It has, however, another important advantage, namely, its ability to operate at higher speeds due to the positive motion of the sleeves. This feature will become particularly important whenever engine operating speeds exceed the capabilities of the spring-returned poppet valve now in general use.

The development of the single-sleeve valve has been relatively slow due primarily, I believe, to the difficulty in fabricating suitable interchangeable sleeves. Thanks to the encouragement of the British Air Ministry and the splendid work of H. R. Ricardo and A. H. R. Fedden, there is now widespread interest in the single sleeve valve. It is a foregone conclusion that this interest will greatly accelerate its development and the final evaluation of its merits.

The trend of development of the present standard engines is definitely toward somewhat smaller cylinders operating at higher speeds with greater boost. The results of such development will be smaller, more compact engines which will provide greater thrust power in relation to their form drag. Improved smoothness of operation will be achieved by the use of lighter reciprocating parts and higher crank speeds. These new powerplants will not only insure higher airplane performance but also longer life and lower operating cost. Continuous cruising powers of 700 to 1200 hp. will, no doubt, soon be available from our present engine types, with take-off powers at least 35 per cent in excess of these.

Future Requirements

We must anticipate now the day when power requirements will exceed the capabilities of the existing standard engine types. To do so intelligently requires that we analyze the powers likely to be required and the influence of the powerplant on the aerodynamic efficiency of the airplane as a whole. The total power required is influenced both by the size of the airplane and by the cruising speeds that must be maintained. This relation is illustrated on Fig. 13, which shows power requirements of typical four-engined landplanes of similar design and equal wing loading. It is evident that much greater power will be required whether the trend is toward larger airplanes cruising, let us say, at 200 m.p.h., or to somewhat smaller craft to be operated at higher speeds. Much greater airplane speeds can be provided, but there is a question as to whether such equipment could be made profitable. A balance must be struck among speed, size, and revenue, as has been the case in other forms of transportation. It is not my intention to prognosticate on the rate of airplane development, but simply to show by this brief review the imminent need for engines of considerably greater power.

Number of Engines per Airplane

Engine size is influenced by the number per airplane, whereas the power required per engine in a particular airplane depends both on the schedule to be met and on the safety factor. Dependable service is synonymous with reserve power. Lines with schedules requiring over 80 per cent of the rated power of the engines are late 50 per cent of the time, while the periods between overhauls are more or less inversely proportional to the percentage of power used. This situation has led to designing the new equipment so that it will normally meet the required schedule with 65 per cent of the rated power. The reserve power thus provided is the best possible insurance for maintaining schedules under adverse weather conditions. Two engines are, in my opinion, the very minimum that should be employed in transporting passengers, as the minimum requirement for safety is at least 50 per cent

[5] See S.A.E. TRANSACTIONS, August, 1935, pp. 301-306; "An Automatic Power and Mixture Control for Aircraft Engines," by Guy E. Beardsley, Jr.

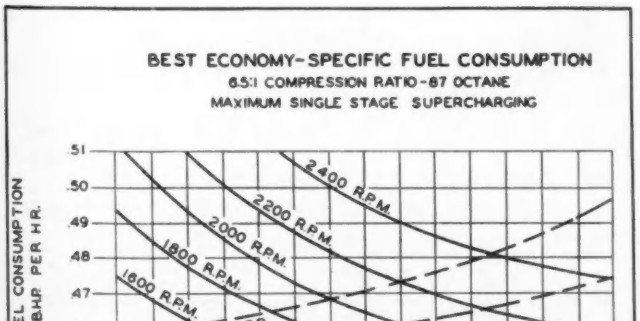


FIG. 12

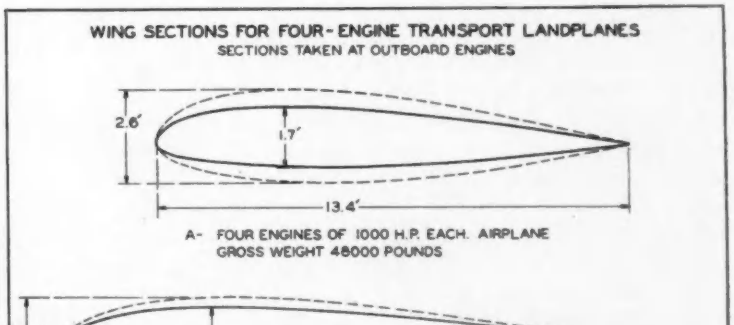


FIG. 14

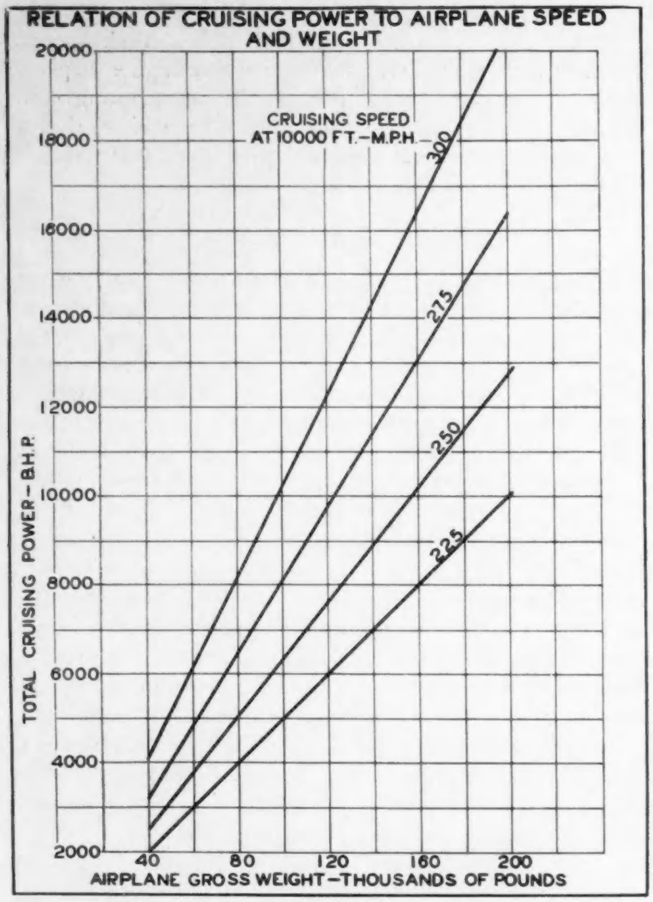


FIG. 13

of the total engine power at all operating altitudes. A four-engined machine designed to meet the required schedules with 65 per cent of its rated power has 15 per cent reserve for bad weather with one engine dead. Six engines may ultimately be preferred for transoceanic service on account of the added safety. Design considerations also may favor this arrangement as it permits of better distribution of load and stress in the wing, as well as of minimizing the weight and size of the propellers. The take-off conditions are improved definitely since there is a more complete coverage of the wing area with slipstream.

Assuming that land transports of at least 100,000 lb. will be required in the not-too-distant future with cruising speeds of at least 225 m.p.h., or somewhat smaller craft cruising at higher speeds, a total cruising power of 5000 b.hp. is needed. This means that engines of at least 2300 take-off hp. will be required, based on four per airplane and on the present practice of cruising with 65 per cent of rated power. Even larger engines are likely to be required in the same period for flying boats. The importance of take-off power on the amount of payload which may be carried has led us to give each engine a take-off rating of approximately 20 per cent in excess of its standard rating. Normally this power is required but for a few minutes, but I feel that its use should not be limited in an emergency and that it should be available at the highest fields on the route.

Powerplant Drag

Operators, although keenly aware of the advantages of low specific consumptions, sometimes overlook the much more significant index of fuel expense and weight per ton-mile. The total power being employed to maintain the schedules is, after all, likely to influence fuel costs and weight even more than does the specific consumption. The airplane itself is now particularly clean, so that what hitherto were minor losses have become major. In this category are the form and cooling drags of the powerplant. Our studies show that these two items absorb approximately 25 per cent of the thrust horsepower for a 48,000-lb. airplane with air-cooled engines and conventional cowls and a cruising speed of 225 m.p.h. at 10,000 ft. Form drag depends largely on the cross-sectional area of the cowl surrounding the engine. Consequently, it seems reasonable to suppose that the form drag of the radial is greater than that of the in-line in the relation of perhaps 3 to 1. On the other hand, the cooling surfaces for the radial are part of the engine itself, whereas liquid-cooling requires a separate radiator which may add not only cooling drag, but form drag as well. In most installations to date these additions make the total powerplant drag of the liquid-cooled engine practically as great as that of the air-cooled.

The engine form drag can be nearly eliminated by placing the engines entirely inside the wing. Unfortunately, the wing-thickness and taper ratios of modern airplanes, as dictated by aerodynamic and structural considerations, do not provide sufficient room, particularly for the outboard engines. This condition is illustrated on Fig. 14 which shows wing cross-sections at the outboard engines for two land transports with four engines of a total of 4000 and 8000 hp. respectively. The solid lines represent normal sections, and the broken lines show the airfoils that would be necessary to house suitable engines. As will be seen from the dimensions, there is insufficient room for even the flattest of powerplants within the normal wing section, although this difficulty diminishes as the airplane becomes larger. The situation is somewhat better in the case of flying boats with their higher power loadings. A possible solution for the landplane is the use of thicker sections which will increase the local profile drag of the wings by about 30 per cent for the smaller ship and 15 per cent for the larger, but since the entire wing need not be made deeper, the average profile drags will rise by only about 12 and 6 per cent respectively in the two cases. The approximate effect on power required at constant cruising speed would be represented by an increase of 4 per cent for the smaller airplane and 2 per cent for the larger. The engine form drag, although eliminated, is replaced by the drag of the propeller support, which is estimated to absorb 4 per cent of the power. Taking this item into consideration and allowing for the added thickness of wing necessary in the two cases, the powerplant should be charged with 8 per cent of the thrust horsepower for form drag in the smaller ships and 6 per cent in the case of the larger.

It should be noted that, even after thickening the wings materially to accommodate the powerplants, there is still insufficient room to permit reaching the engines during flight, much less doing any work on them. I believe that this arrangement will be practicable only when wing thicknesses of 5 or 6 ft. can be employed. However, continued improvement in high-lift devices and consequent reduction in wing area are constantly making this problem more difficult.

The disadvantages of placing the engines inside the wing are primarily due to the disturbing effect on normal balance resulting from moving the engines so far aft, to the effect on the wing structure, and to the impaired engine accessibility. Despite these disadvantages, the reduction in operating cost may be sufficient to warrant serious consideration of ways and means of overcoming them. These problems probably will solve themselves in the larger ships of the more-distant future.

Granted that it is now impracticable to place the engines inside the wing, there are still opportunities for materially reducing the form drag. The propeller should be located for aerodynamic considerations approximately one-half its diam-

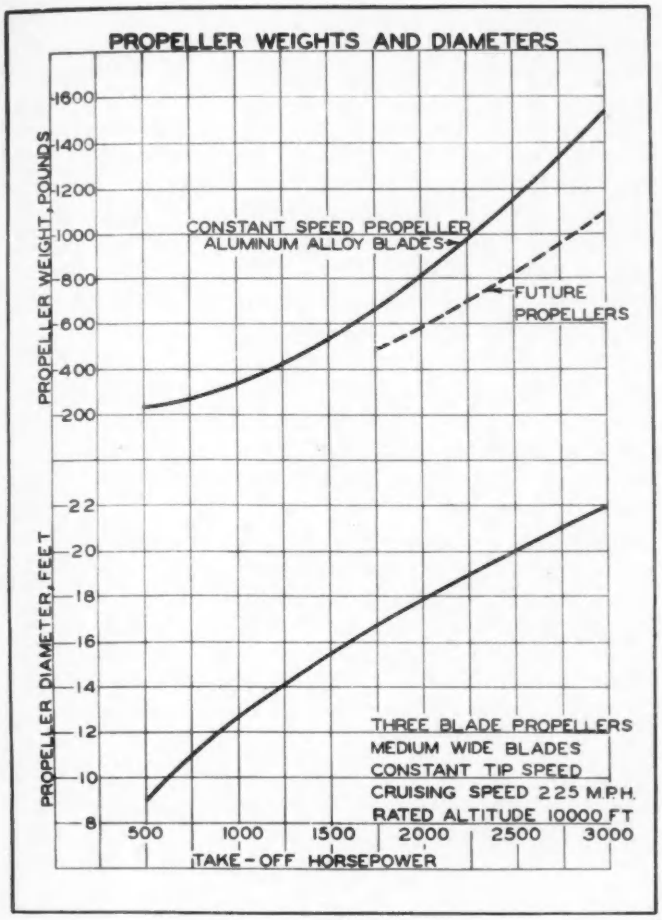


FIG. 15

eter ahead of the wing. The "wetted surface" of the nacelle is then a function of propeller location rather than of engine length. In any case some sort of supporting structure is required which must be both rigid and suitably faired into the leading edge of the wing, and such a structure, if of proper size and shape, actually improves the propulsive efficiency. This condition would indicate that the best alternative to submerging the engine in the wing would be to reduce its cross-section to the minimum and utilize it as the propeller support. Such an engine with small cross-section would necessarily be long. Engine length, however, is not, after all, a factor since there is ample room for even the longest in-line engine between the propeller and the forward wing spar, or the box in monospar construction.

Concerning cooling drag, it must be realized that its accurate segregation from form drag requires that it be defined in terms of a cooling power equal to volume flow of cooling air multiplied by pressure drop through the engine or radiator. Bench tests indicate that the requisite engine operating temperatures could be maintained by the expenditure of only 2 or 3 per cent of the brake horsepower, either for a radial engine under a conventional low-drag cowl or for a liquid-cooled engine with a conventional radiator. Unfortunately, this low cooling drag cannot be had for the radial engine without its high form drag. In the case of the liquid-cooled system it has been customary to add form drag to secure the requisite cooling, as in the case when external tunnel radiators are used. The ideal solution is the use of surface or wing radiators as exemplified in racing airplanes. This arrangement does not entirely eliminate cooling drag, since some additional wing area is required to take care of the greater weight of such a system. The cooling drag should be charged with a minimum of 2 per cent of the thrust horsepower after allowing for the additional weight, including that of the auxiliary radiator needed to deal efficiently with take-off power for a prolonged period.

Recent radiator developments indicate that form drag may be eliminated by submerging the radiator in the wing or fuselage. This design, coupled with low-resistance cores, may reduce the radiator drag to one-third of the combined form and cooling drag of the external tunnel radiator. This reduction would make the cooling drag comparable to that of the air-cooled engine if no scoop were necessary, although the improvement is not quite so marked after due consideration is given to the additional wing area necessitated by the greater weight of the liquid-cooled system. The reported cooling-system weights for high-temperature cooling vary considerably, but 0.30 lb. per hp. seems a fairly representative figure. It is estimated, therefore, that a minimum of 5 per cent of the thrust horsepower would be required to overcome the cooling drag. Surface radiators, of course, will become less attractive if it is possible to achieve this theoretical figure with the submerged radiator.

Considerable progress is being made meanwhile in improving air-cooling technique. The actual cooling drag of the present standard air-cooled installation with low-drag cowl requires from 5 to 6 per cent of the thrust horsepower. As previously indicated, it has become necessary to increase the mass flow of air over the cylinders to obtain satisfactory cooling with the higher outputs, but further refinements in cowl shape and air passages nevertheless give promise of additional reductions in drag, particularly at cruising speeds. It seems probable that the required cooling drag for air-cooled engines of small frontal area used as propeller supports or totally submerged in the wing would be on the same order as that required for liquid-cooled engines with submerged radiators. This conclusion is reached on the assumption that a forced flow of cooling air could be provided in which the entrance and exit for the cooling stream were so designed and located as not to cause interference or form drag. The total powerplant drag in such cases would then be influenced principally by the cross-section of the engine and its effect on the form drag.

It should be noted that, despite the periodical controversy over the merits of air- and liquid-cooling, the performance of similar airplanes with the two systems has been comparable. Improved radiators and better location are reducing the drag of the liquid-cooled system. It is possible that this improvement will be offset by the decided reduction in frontal area afforded by the two-row air-cooled engine and the improvement in cooling technique. In any event, there is a decided opportunity for reducing the powerplant drag with both the air- and liquid-cooled types of engine. It seems reasonable to expect that at least half of the drag of present commercial installations can be eliminated, which will mean a reduction in power required of some 12 per cent.

Propellers

A propulsive efficiency of 88 per cent, although possible of achievement under proper conditions, is impaired readily, with consequent penalty to operating expense. It is, therefore, important to provide adequate propeller diameter and properly designed blades turning at the most efficient speed and in the optimum location. The curves of Fig. 15 give an idea of the appropriate diameter and weight of suitable three-blade constant-speed propellers for airplanes cruising at 225 m.p.h. at 10,000 ft. with 60 per cent of their take-off power. Taking the case of an engine with 2000 take-off hp., it will be seen that an 18-ft. propeller is required, which weighs

approximately 800 lb. The curves of Fig. 15 show that the weight of metal propellers is increasing rapidly with diameter. For this reason, intensive development work is being carried on which gives promise of reducing this weight by approximately a third, as shown by the dash line. The diameter of the propellers required by the large engine is sometimes disturbing to airplane designers accustomed to thinking in terms of much smaller sizes. The increasing airplane size, as indicated by Fig. 16, tends to offset the disadvantages that might at first be contemplated.

Various arrangements have been proposed to reduce the distance from the centerline of the airplane to the outboard propeller, such as gearing two or more engines to one shaft or employing double-concentric propellers. The use of a single large propeller driven by two or more engines gives the maximum propeller diameter and weight. The double-concentric arrangement gives the minimum propeller diameter and weight. Unfortunately, the take-off thrust is impaired seriously because of the inadequate disc area. The most efficient arrangement seems, therefore, to be a single propeller of adequate diameter for each engine.

Weight

The weight of the complete powerplant contributes to the total drag of the airplane due to its influence on wing area. Weight alone, however, is not the true criterion, but rather its effect on the overall efficiency of the airplane. The constant-speed propeller is illustrative of this point, since it weighs 20 to 60 per cent more than the fixed-pitch propeller but permits taking off 10 to 30 per cent greater gross weight.

The dry engine weight of a modern air-cooled transport engine complete and ready to run, as equipped for commercial service, is approximately 1.30 lb. per take-off hp. I gather from the published data on liquid-cooled engines that a comparable figure for them is 1.60 lb. per take-off hp. In this connection it may be noted how little the engine weights for a given power are influenced by type, providing each is thoroughly developed for the same service. Actual dry weights of nine- and fourteen-cylinder air-cooled, as well as of vee and flat twelve-cylinder liquid-cooled engines are, as a matter of fact, quite comparable, probably due to the difference in displacement required. Some astonishingly low weights have been published but experience indicates that the weights come into line as these powerplants are developed to give satisfactory service. The specific weight has decreased slowly in recent years, as indicated by Fig. 2, due to the addition of propeller reduction gears and superchargers, and the insistence on longer periods of operation between overhauls.

I see no real opportunity for materially reducing the specific engine weight at the moment. As a matter of fact, it may be necessary to increase it to secure the minimum cruising fuel consumption. On the other hand, it is a foregone conclusion that, if such increases are adopted, they will be justified by reducing the operating cost per ton-mile.

Summing up the future requirements, it is evident that we must be governed by the present demands and past trends as to the powers likely to be necessary. Some operators are already thinking in terms of 1500- to 2000-hp. engines. This thought might be interpreted to mean that such engines will be needed within the next 5 years, while powerplants of twice these powers are not far off if the recent trends are continued. The analysis of powerplant drag shows the importance of making these big engines of such shape that they may be stowed away in the wings or, where this location is not practicable, that they will have the minimum form drag when acting as propeller supports. With these points in mind it would seem in order to consider the requisite engine types.

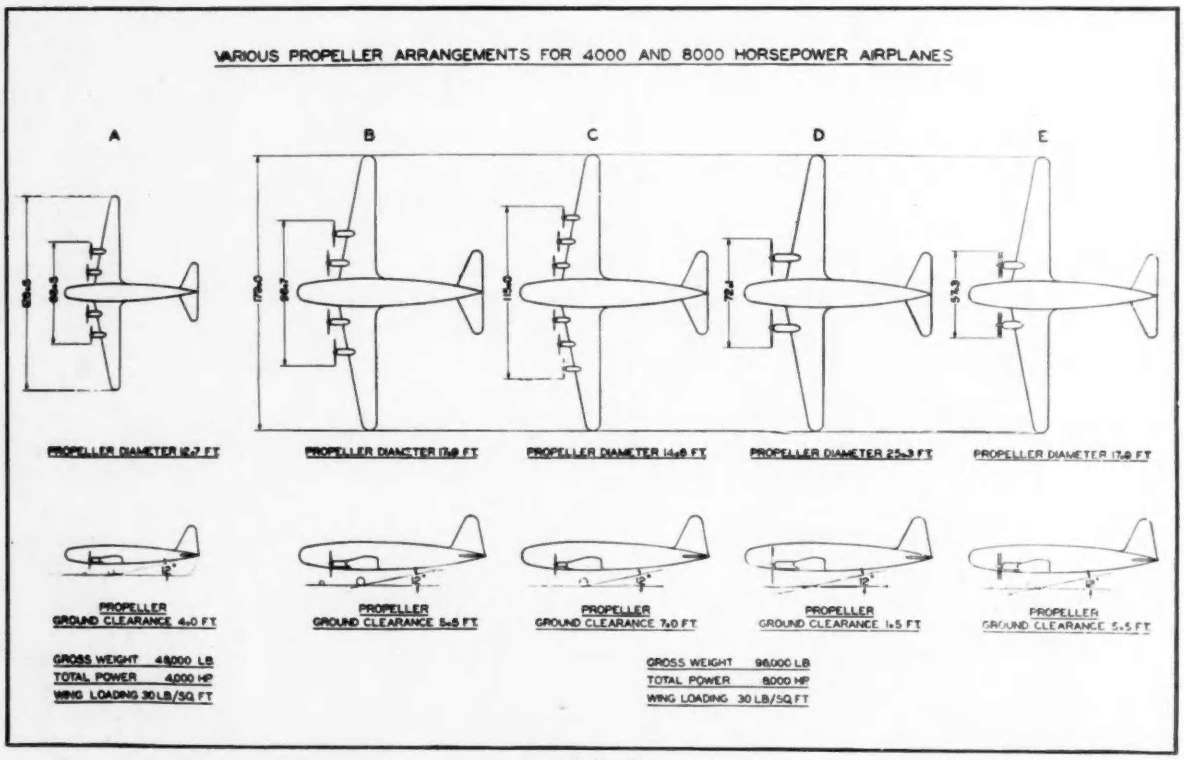


FIG.16

Engine Types for Greater Output

Engine development to date has been concerned mainly with the in-line and the radial. Adherents of the former type

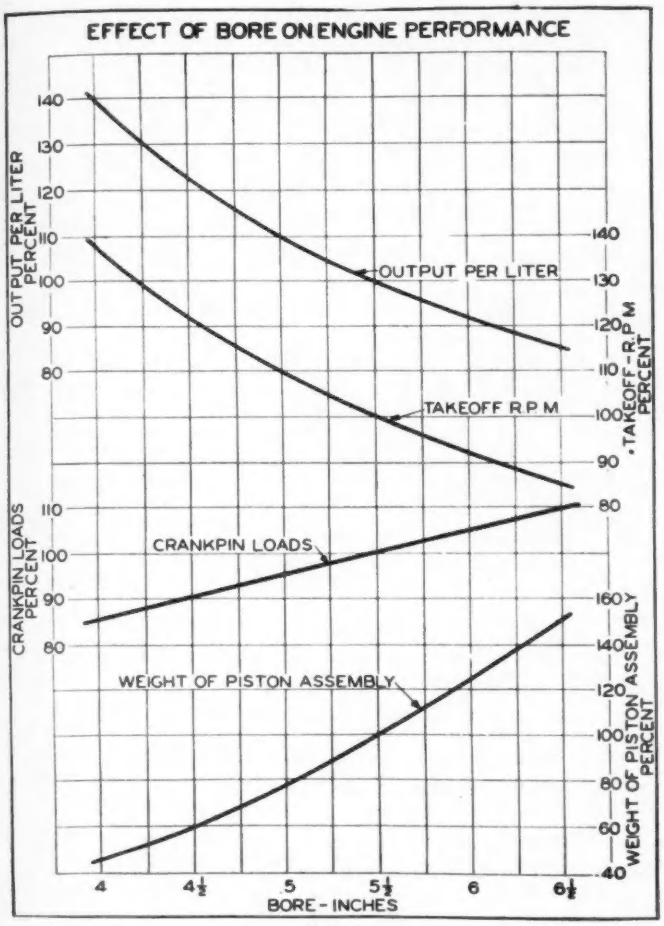


FIG. 17

have worked on the principle of the maximum number of crankpins per shaft, while the latter proponents devoted their initial efforts to the maximum number of cylinders per crankpin. The requirements for greater power and, consequently, more displacement have forced both groups to the consideration of other types in which a greater number of cylinders can be employed. This consideration has raised the question of the optimum size of cylinder, the number that may be used per engine, and the cylinder arrangement.

Cylinder Size

Cylinder dimensions are a compromise between displacement and operating speed to secure the maximum output per liter consistent with reasonable cost. The maximum size of cylinder probably already has been reached, and the trend is definitely toward smaller bores, as previously noted. The fundamental advantage of the smaller cylinder is its greater output per liter, as shown in Fig. 17. This increase is primarily due to the reduction in the reciprocating weights which reduction, in turn, permits higher operating speeds. A further advantage lies in the improved cooling resulting from the shortening of the heat-flow paths. This improvement permits greater boost for a given fuel and consequently still further increases the output. No attempt has been made to evaluate this factor in the curve because we have as yet inadequate information on cylinders of similar design covering a sufficient range of bore. In view of the experience gained in building engines with cylinders ranging in bore from 5 in. to 6¼ in., I am of the opinion that the 5½-in. cylinder makes the best compromise at present between output and cost. This size is, therefore, considered as the optimum in the following discussion of engine types. It is helpful, in this connection, to consider an output of 100 hp. per cylinder. This value is equivalent to 47 hp. per liter, which will no doubt be achieved within the next five years. The trend undoubtedly will be toward even smaller cylinders, as their increased performance justified the added cost.

Connecting-Rods

The number of cylinders per pin is determined by the permissible connecting-rod design and by the crankpin bearing loads. Nine cylinders are the most that can be used effectively with a solid master rod. Seven cylinders are the limit with a split rod due to the lack of cross-section between the split and the adjacent knuckle pins, as well as to the difficulty of making satisfactory provision for the clamping bolts. This condition is illustrated on Fig. 18, showing the evolution of our two-row master rods. The permissible number of cylinders is also influenced by the crankpin loads, particularly as the operating speeds are raised; this consideration tends further to reduce the number of cylinders per pin.

Crankshafts

Present practice indicates that at least six throws per shaft may be used satisfactorily. However, even the six-throw shaft

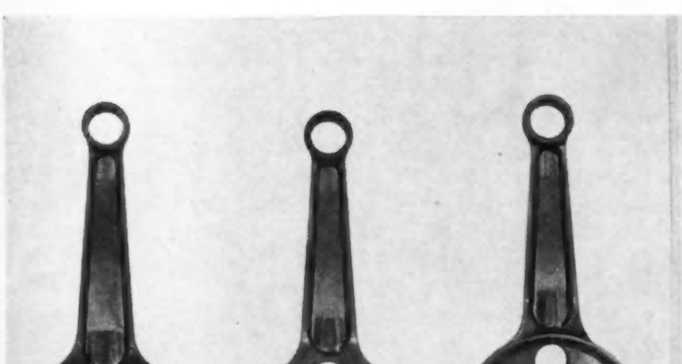


Fig. 18 – Connecting-Rod Evolution

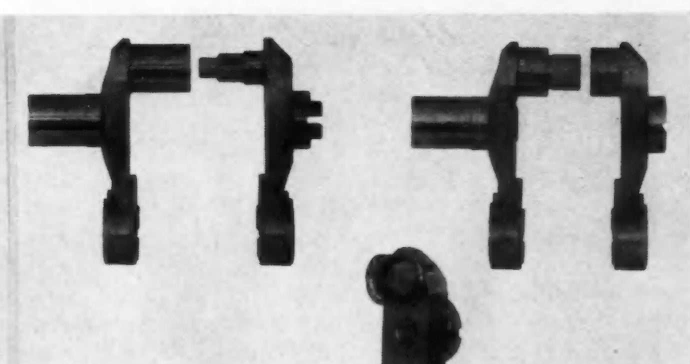


Fig. 19 – Comparison of Crankshafts

presents a difficult problem in an engine of high power due to torsional vibration. This condition is improved somewhat where a relatively large number of small cylinders is used, operating at high crank speeds. The fact remains that the forces are considerable and that the wind-up in the shaft is proportionate to its length. For this reason, a greater number of throws still further complicates the problem. Failures of crankshafts, reduction gears, accessory drives, and even propellers have led to a thorough study of the torsional vibration

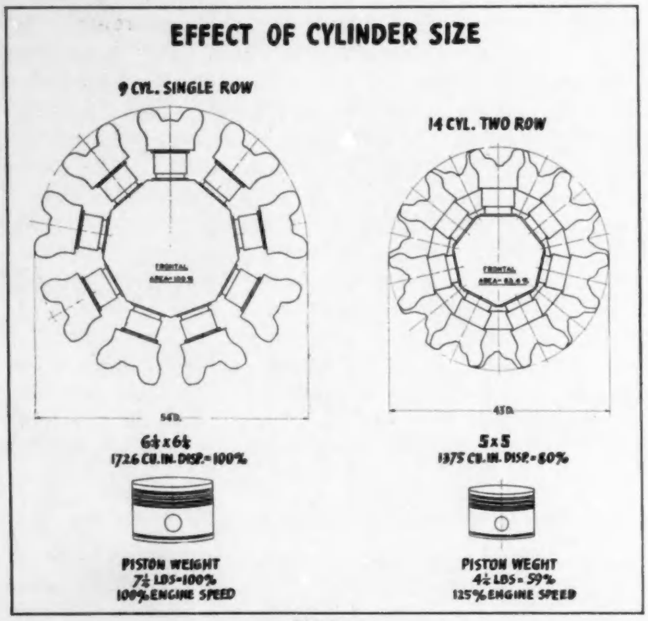


FIG. 20

problem. In the United States we are working to variations of $\pm\frac{1}{2}$ deg. within the operating range of speeds and powers of our single- and two-row engines. It is doubtful whether sufficient experience has yet been accumulated to say definitely whether this requirement is too severe or not. All we do know is that the torsional-vibration difficulties previously experienced have disappeared when working within these limits. Presumably somewhat larger variations will have to be permitted for shafts with a greater number of pins.

A built-up crankshaft would permit the use of a greater number of cylinders per pin providing such a shaft could be made equivalent to a solid one. Our experience with built-up single-throw shafts may be of interest in this connection. The original and latest designs are shown in Fig. 19. Although the original shaft was satisfactory for 400 hp., failures were experienced in the rear cheeks as the rating was increased, and galling or fidgeting caused cracks in the mating surfaces. To overcome these defects, the design was revised as shown, including the introduction of vibration dampers consisting of steel rollers inserted in somewhat larger cylindrical openings in the counterweights. Shafts of this design give every indication of lasting the life of the engine, even though the power has been increased by nearly 50 per cent. Another type of split single-throw shaft is exemplified in the Bristol clamp type. It should be noted that, in both of these arrangements, comparatively little torque is carried through the split. With two or more throws, a considerable amount of torque will have to be transmitted from one portion of the shaft to another. Experience, especially in service, is as yet too limited to evaluate the capabilities of the built-up multi-pin shaft.

Balance and Torque

Good mechanical balance and uniform torque are essential in any engine. These factors are becoming more important with the larger powerplants on account of their effect on the

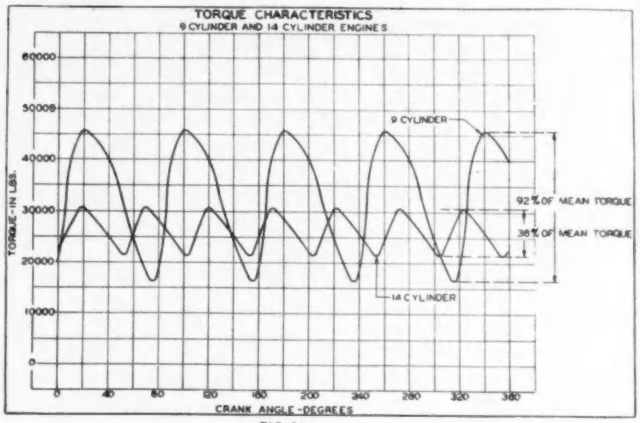


FIG. 21

life of the engine and the propeller. Propellers which have satisfactory fatigue characteristics when run with an electric motor have to be made considerably heavier to give equal durability when driven by an internal-combustion engine of the same power. Torque variations also have been found to have a decided influence on propeller life; this means that the propeller weight can be reduced with an increased number of cylinders.

Number and Arrangement of Cylinders

The most satisfactory powerplant from the standpoint of all-around performance and operating cost is that with the requisite number of optimum-size cylinders for the given output. The use of the minimum number of maximum-displacement cylinders, although reducing the first cost, gives a comparatively rough-running engine with a shorter life and usually with the maximum frontal area.

The effect of the number of cylinders on displacement and frontal area may be illustrated by the concrete case of a nine-cylinder single-row versus a fourteen-cylinder two-row, both developing the same power with the same mean effective pressure. Assuming that nine 6¼-in. square cylinders are required for the single-row with a total displacement of 1726 cu. in., it will only be necessary to use 5-in. square cylinders in the two-row with a displacement of 1375 cu. in. The reduction of 20 per cent in displacement is due to the increased operating speed of the smaller cylinders. A reduction of 11 in. in diameter is provided by the two-row, or a decrease in frontal area of 36.6 per cent. This comparison is illustrated in Fig. 20. The comparative torque of the two engines is illustrated in Fig. 21, which shows the decided increase in smoothness of the fourteen-cylinder engine.

The method of arranging the cylinders to a large extent determines the cross-section. The arrangement is influenced by the need of good balance, even torque, satisfactory cooling, uniform distribution, and reasonable bearing loads. These requirements may be met with various arrangements of cylinders. The choice ranges from short engines with large frontal area to long engines with small cross-section. Fig. 22 shows four radial combinations of the optimum cylinder and three in-line arrangements. The frontal areas are indicated in per cent of that of the nine-cylinder radial which gives the greatest displacement per crankpin for its projected area. It should be noted that the form drag of the radial types is influenced by cylinder size and not particularly by the number of cylinders per row, whereas the drag of the in-line engine is affected by the number of banks, in addition to the cylinder size. Since the total number of cylinders is not a factor, it follows that the form drag of the larger engines is comparatively small per horsepower. The radial combinations lend themselves to use as propeller supports, due to their cylindrical shape, whereas the more rectangular cross-section of the H and X arrange-

ments makes them desirable for submersion in the wings. Radial combinations of at least thirty cylinders appear feasible, whereas in-line engines of twenty-four cylinders already have been built. Undoubtedly, ways and means can be found to employ even greater numbers of cylinders whenever they become necessary.

Multishaft Engines

Greater power may be secured by the combination of two or more engines in a single unit. Two ways of accomplishing this combination are illustrated by the Fiat racing engine, type AS-6, and the Napier Halford Dagger. The Fiat is virtually 2 twelve-cylinder engines placed back to back with a gear box between them. Two concentric propellers, one for

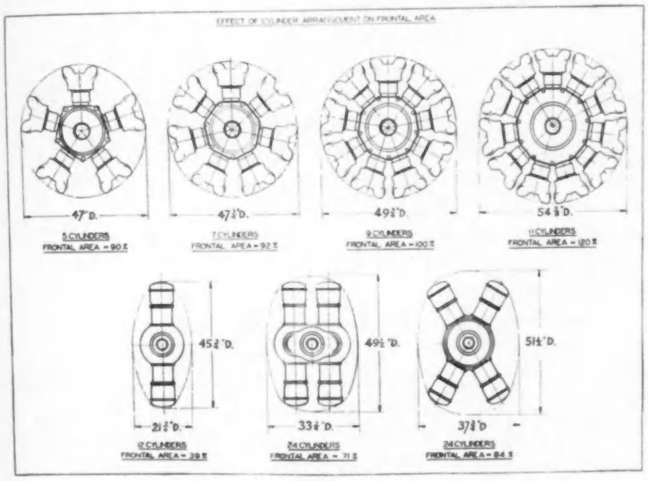


FIG. 22

each engine, are driven through offset gearing and concentric shafts. In the Napier we have a combination of two flat twelves united by a common crankcase and driving a single propeller through spur gears. Both of these arrangements furnish means of utilizing a greater number of crankpins and therefore increasing the displacement and, consequently, the output.

Conclusion

The general trend in engine development continues steadily toward ever-increasing outputs per liter, with the consequent effect of improving the take-off powers and reducing the engine size in the geometric sense. There is reason to believe that the rate of progress of the past decade can be maintained, providing our invaluable allies – the chemist, the metallurgist, and the fuel technician – can keep pace with our needs.

The development of the present standard types definitely tends toward smaller cylinders for the higher outputs. This trend, combined with the general acceptance of the two-row type for the higher powers, has effected a decided reduction in frontal area per horsepower. From the standpoint of performance, take-off powers of 1500 to 1800 hp. seem feasible in the period immediately ahead. The ever-increasing importance of operating costs has concentrated attention on this most vital performance characteristic. As a result, great strides have been made in reducing the specific fuel consumption, and there is evidence that service consumptions of 0.40 lb. per b.hp-hr. may be achieved within the next few years.

The evident future needs for engines of from 2000 to 3000 hp. has focused attention on other types in which additional displacement may be provided through the employment of a greater number of cylinders. Two new engine types may result, namely, the cylindrical or multirow radial and the rectangular or flat multibank in-line. The form drag of these types need be no greater than for present-day powerplants, despite their decidedly greater output.

Continued improvement in engine cooling has reduced the drag of both the air- and liquid-cooled systems and there appear to be still further opportunities of betterment. The combined reductions in powerplant drag may well result in cutting the fuel bill by as much as 10 per cent which, combined with a possible further improvement in specific consumption, gives hope of a net saving of 15 to 20 per cent.

There is every reason to believe that our future engine, as well as airplane, development must continue to be a steady step-by-step process, keeping pace with our knowledge, rather than a sudden advance in much larger equipment. As in the past, each gain must be consolidated by thorough and painstaking tests before further progress is feasible both from an economic and an engineering standpoint. The problems confronting the designer are more complex than ever before and require both greater time and greater expense for their solutions. Fortunately, the aviation industry has passed through its pioneering days and is now equipped with personnel and experience to deal effectively with these problems. It may truly be said that aviation has at last settled into its stride. For this reason, I do not hesitate to affirm that powerplant development can and will keep pace with requirements.

In closing, I wish to express my gratitude to the various friends who have aided me with information and their counsel, and especially to members of our engineering staff who have been of such invaluable assistance. I also wish to draw attention to the debt of gratitude that commercial aviation in the United States owes to our Army Air Corps and Naval Air Service. Without their continued support and encouragement our technique would hardly have progressed to the point where such developments as I have outlined would be feasible.

Trend of Air-Cooled Aero Engines

(Continued from page 454)

criticism on this score, but they have been put forward only as a basis of discussion. It is appreciated that wing design is dependent upon a number of factors, such as type of construction, speed, operational altitude, and so on, and, in this connection, it will be useful if some advice can be given as to the trend of wing thickness for the future, as it seems that this factor may have a considerable bearing on engine layout.

To sum up, during the next five years, it would appear that the smaller the size of the aircraft, the more difficult it is to obtain a suitably scaled radial or in-line engine of sufficient power whereas, the larger the size of the aircraft, the less it seems can be said against the radial, in fact, in the largest category, the engine is almost entirely lost in the section of wing.

The wetted surface of a ducted radial engine of this size must be a very small proportion of the total wetted surface of the aircraft. Such engines would be required for a large civil flying boat or long range bomber, cruising at 250 to 275 m.p.h., and it is assumed that the thickness of wing shown in the diagram would be quite permissible.

So much for my summing up of the possible layouts for the four sizes of air-cooled aero engines required for the next five years of aircraft development. I have endeavored to be unbiased in this analysis, and have made it with the hope of obtaining constructive and helpful criticism from the aircraft designer, as it is believed that every engine designer is anxious to learn all he can before finalizing his new series of engines for 100-octane fuel.

I should like to proffer my thanks to the Bristol Aeroplane Co. and others for permission to show slides, and to members of my staff for helping me, especially Messrs. Mansell and Copley in the preparation of diagrams and tabulations.

Laminar and Turbulent Boundary Layers as Affecting Practical Aerodynamics

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THE main part of this paper deals with one of the unsolved problems that impede further progress – the aerodynamics of airfoil sections in relation to further research. In studying laminar and turbulent flow, special consideration is given to determining where the transition from one to the other takes place along the airfoil surface.

With no equipment capable of studying the subject experimentally in the higher full-scale range of Reynolds numbers, the problem has been attacked theoretically by two methods: According to the first method, the laminar boundary layer is supposed to become unstable.

With the second method of attack the mechanism of transition is supposed to be something like separation. This comparison has the advantage that the separation phenomenon is comparatively well understood and can be dealt with quantitatively by means of existing theory. Separation and its relation to the transition phenomenon are therefore considered, and the actual behavior of the flow during its change from laminar to turbulent is illustrated.

The final conclusion reached, however, is that we do not know but should find out whether theoretical gains indicated are possible. Such investigation will require suitable equipment capable of reaching these very large Reynolds numbers.

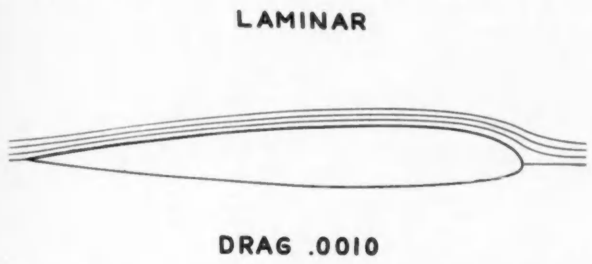
RECENT progress in the most important field of practical aerodynamics, the flow about wing sections, is due to an appreciation of the character of the flow as affected by variations of the section shape, the scale or Reynolds number of the flow, and the turbulence of the air stream. This progress has resulted in the development of improved wing sections, greater accuracy in the derivation of airfoil *section* characteristics from the usual airfoil tests, improved methods of predicting the section characteristics to be expected in flight at other Reynolds numbers and other conditions of turbulence than those under which the characteristics were measured and, finally, improved methods of predicting complete wing characteristics from the basic section characteristics.

This paper, however, deals with one important unsolved problem that stands in the way of further progress. Our lack of knowledge about the boundary layer constitutes the main difficulty. Two types of boundary layer are encountered which, owing to their entirely different character and behavior, markedly influence the final practical aerodynamic characteristics of airfoil sections. These two types of boundary layer are known as "laminar" and "turbulent." Figs. 1(*a*) and 2(*a*) show the two types as they might be imagined to occur on the upper surface of an airfoil section in flight (inasmuch as the complete laminar boundary layer could not actually exist but would separate from the airfoil surface). The very low resistance to separation as compared with the turbulent boundary layer is, in fact, one important characteristic of the laminar layer. Both types of boundary layer are shown as they would develop on a flat plate where separation would not be involved. The other important respect in which the two boundary layers show a marked difference is indicated by the numbers in Figs. 1(*a*) and 2(*a*) comparing the drag coefficients and by the skin-friction-drag variation with Reynolds number shown in Figs. 1(*b*) and 2(*b*).

A very large scale or Reynolds-number range is encountered in practical aerodynamics. Most of the figures presented herein such as Fig. 1(*b*) show a thousand-fold range of the Reynolds number, that is, from 100,000 to 100,000,000. The three main divisions shown on the plots, each representing a ten-fold range, have been indicated in Fig. 1(*b*) as "small tunnel" (100,000 to 1,000,000); "large tunnel" (1,000,000 to 10,000,000, which also covers the lower full-scale range including the landing conditions for existing transport airplanes); and "full scale" (10,000,000 to 100,000,000, which corresponds to the large future airplane or flying boat having a wing chord of 40 ft. and flying at 260 m.p.h.). The important result shown in Fig. 2(*b*) then is the greatly reduced drag, corresponding to both types of boundary layer as these higher full-scale values of the Reynolds number are approached, and the increasing difference between the two, the laminar drag becoming almost insignificant in the higher full-scale range. In this range it obviously makes a great deal of difference in the drag whether the boundary layer is laminar or turbulent.

In general, both types are observed; the laminar appears over the forward part of the airfoil and changes to the turbulent somewhere along the airfoil surface at the so-called

[This paper was presented at the National Aeronautic Meeting of the Society, Washington, D. C., March 12, 1937.]



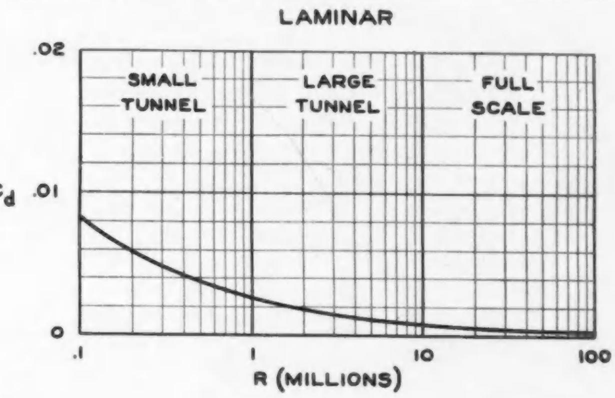


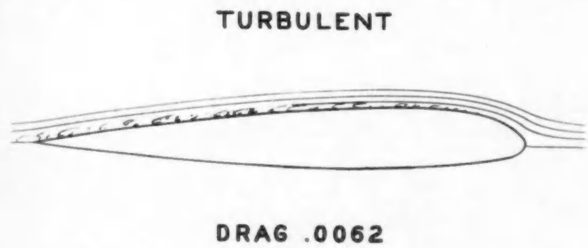
Fig. 1a (*above*) – **Representation of Laminary Boundary Layer on the Upper Surface of an Airfoil**

Fig. 1b (*right*) – **Variation of Laminar Skin-Friction Drag Coefficient with Reynolds Number**

"transition point" (Fig. 3(*a*)). Owing to the difference in the character of the laminar and turbulent boundary layer, it is clearly essential to consider where the transition from one to the other takes place.

The classic studies by Osborne Reynolds of the flow in pipes showed that transition occurs at a certain value of the ratio we now know as the Reynolds number, dependent on the steadiness of the flow entering the pipe. When the transition occurs in the boundary-layer flow along a flat plate at a given Reynolds number (based on either the boundary-layer thickness or the distance of the transition point from the leading edge of the plate), the actual variation of the skin-friction drag with scale is presumably something like that shown in Fig. 3(*b*). Likewise, as Reynolds found in his pipe experiments, the transition occurs earlier or at a lower Reynolds number if the air stream flowing over the plate is unsteady or turbulent. The effect of this early transition on the skin-friction drag coefficient, c_d, of the plate is shown in Fig. 4.

Experimental results in general confirm this view of the subject but, as shown by Dryden[1], who has obtained transition points ranging between those indicated by the numbers 2 and 3 in Fig. 4, pressure variations along the plate also have a very important effect. Roughness of the plate or a poor nose form may also introduce turbulence and thus hasten transition, even to the extent indicated by curve 6 in Fig. 4, which corresponds to transition at the leading edge and shows no effect of a laminar boundary layer. Finally, when airfoils are considered, the study of the occurrence of transition is complicated further by the presence of large variations of pressure along the surface and, possibly, by the curvature of the streamlines. Nevertheless, thin airfoils, which are asso-



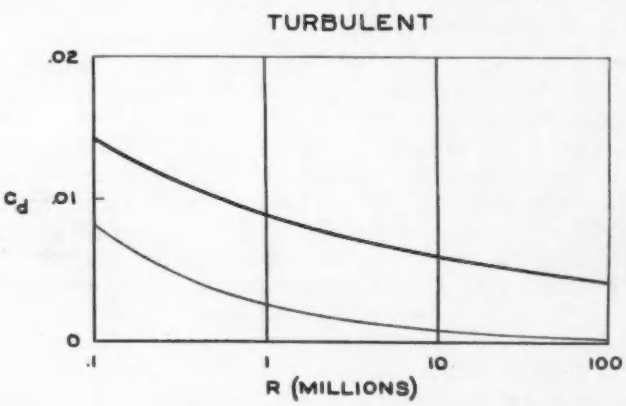
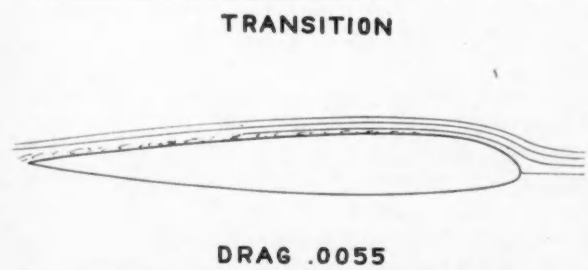


Fig. 2a (*above*) – **Representation of Turbulent Boundary Layer on the Upper Surface of an Airfoil**

Fig. 2b (*right*) – **Variation of Turbulent Skin-Friction Drag Coefficient with Reynolds Number**

[1] See N.A.C.A. Technical Report No. 562, 1936; "Air Flow in the Boundary Layer Near a Plate," by Hugh L. Dryden.



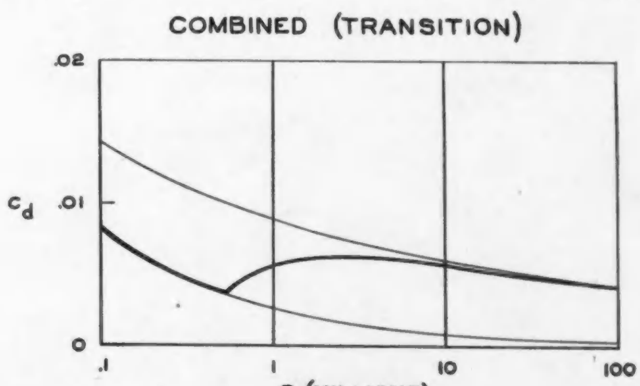


Fig. 3a (*above*) – **An example of the Combined Laminar and Turbulent Boundary Layers on the Upper Surface of an Airfoil Showing the Transition Point**

Fig. 3b (*right*) – **An Actual (Combined Laminar and Turbulent) Variation of Skin-Friction Drag Coefficient on a Flat Plate**

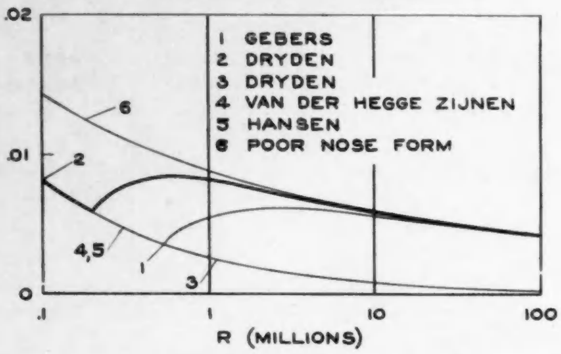


Fig. 4 – Skin Friction Variation with Reynolds Number on Flat Plate with Increased Turbulence – The Numbers Indicate Approximately Where Transition Was Encountered by Different Experimenters Under Various Conditions

ciated with small pressure variations and curvatures, may at least be compared with flat plates as in Fig. 5. The resemblance to the corresponding curve for the flat plate with increased turbulence (Fig. 4) is striking.

The effects of the increased turbulence in the variable-density tunnel may be taken into account on the basis of an "effective Reynolds number," approximately 2.6 times the test Reynolds number at which scale the corresponding transition conditions might be expected to occur in a turbulence-free stream. The turbulence factor, 2.6 for the variable-density tunnel, was determined as shown in Figs. 6 and 7 by a comparison of airfoil maximum-lift measurements in the tunnel and in free air. (The free-air results are actually inferred from tests in the N.A.C.A. full-scale tunnel). An interpretation of the drag on the basis of the effective Reynolds number with an allowance[2, 3] for the reduced skin friction at the higher Reynolds number results in a curve (Fig. 8) that is much like the well-known Gebers curve, representing the drag of a flat plate towed in water; moreover, thick airfoils (Fig. 9) have higher drag coefficients but appear to show similar variations with the Reynolds number. On this basis airfoil results from the variable-density tunnel may be extrapolated into the higher full-scale range as indicated by the dotted line in Fig. 9.

Up to this pont the results, as corrected for tunnel turbulence, seem to be consistent and reasonable, but there remains the question: Do they apply accurately to flight conditions? The difficulty is that the turbulence factor and the effective Reynolds number are determined, in either sphere-drag or airfoil maximum-lift measurements, by the effects of turbulence on transition in a strong adverse pressure gradient in the neighborhood of the separation point, whereas Dryden's results have indicated that small changes of turbulence may produce large changes in the critical Reynolds number for flat plates. *In other words, the drag of a sphere or the maximum lift of an airfoil does not appear to be sensitive to small changes of turbulence as compared with the drag of a flat plate or an airfoil.* Consequently the usual turbulence correction when applied to the drag of an airfoil is likely to be too small. This expectation is supported by the comparison in Fig. 10 of drag results for the N.A.C.A. 0012 airfoil from different tunnels. The rise in drag with increasing Reynolds number, probably associated with a forward movement of the transition point, is seen to occur too early in the more turbulent variable-density tunnel even after the turbulence effect has been allowed for in the usual way by representing both sets of results at their effective Reynolds numbers. Furthermore, the rise is less abrupt in the less turbulent British compressed-air tunnel so that it might be supposed that, in a turbulence-free stream or in free air, the rise would be still more gradual and would occur even later than indicated by the British compressed-air-tunnel results.

It thus appears that the interpretation of airfoil results on the basis of the effective Reynolds number, although it has proved in many instances to be a very useful engineering approximation, represents in reality an oversimplification. Unfortunately this conclusion leaves us without a reliable means of predicting airfoil-drag results, particularly in the higher full-scale flight range. In fairness to the results from the variable-density tunnel, however, it should be noted that drag values are often considered extremely uncertain, in fact sometimes almost indeterminate, in the range where a considerable movement of the transition point may occur. In practice

[2] See N.A.C.A. Technical Report No. 530, 1935; "Characteristics of N.A.C.A. 23012 Airfoil from Tests in the Full-Scale and the Variable-Density Tunnels," by Eastman N. Jacobs and William C. Clay.

[3] See N.A.C.A. Technical Report No. 558, 1936; "Turbulence Factors of N.A.C.A. Wind Tunnels as Determined by Sphere Tests," by Robert C. Platt.

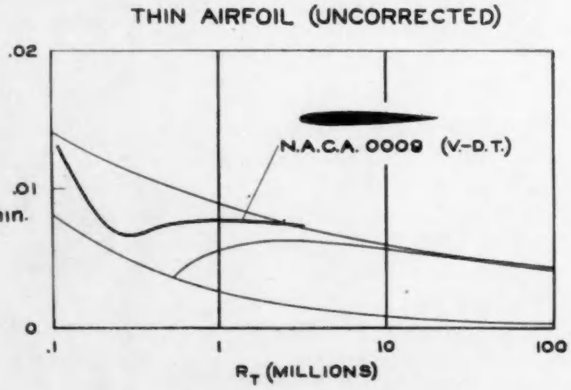


Fig. 5 – Comparison of Airfoil and Flat-Plate Drag

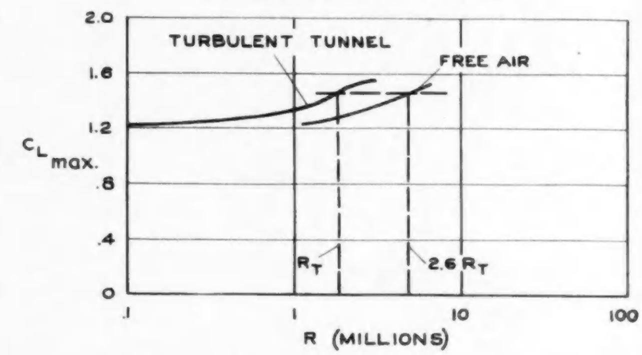


Fig. 6 – Airfoil Maximum Lift as Affected by Tunnel Turbulence

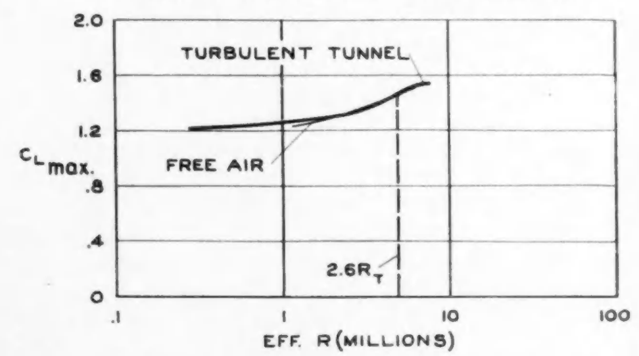


Fig. 7 – Same Measurements as Fig. 6 but Represented as a Function of Effective Reynolds Number

slight roughness, vibration, or induced unsteadiness of the air flow near the airplane wing may bring about transition near the airfoil nose; thus this uncertainty concerning the drag may actually not appear in practice. On this basis the turbulence present in the variable-density tunnel accomplishes the same purpose. The results may thus be considered the most reliable available for *conservative* extrapolations into the higher full-scale range for aerodynamically smooth airfoils.

This consideration brings us, however, to the main subject of the paper. We know very little about why, how, or where transition occurs or, therefore, about the relative extent of the laminar and turbulent boundary layers. Finally, it follows that we have practically no certain knowledge about the two most important airfoil characteristics, $c_{l_{max.}}$ and c_{d_0}, because they are both directly affected by the occurrence of transition.

The situation with regard to the airfoil drag is particularly

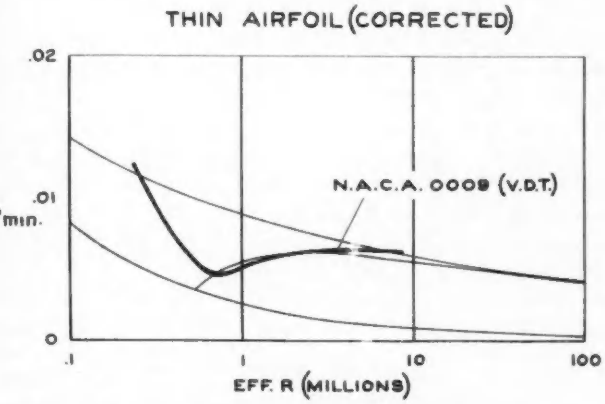


Fig. 8 – Comparison of Flat-Plate and Airfoil Drag Corrected to the Effective Reynolds Number

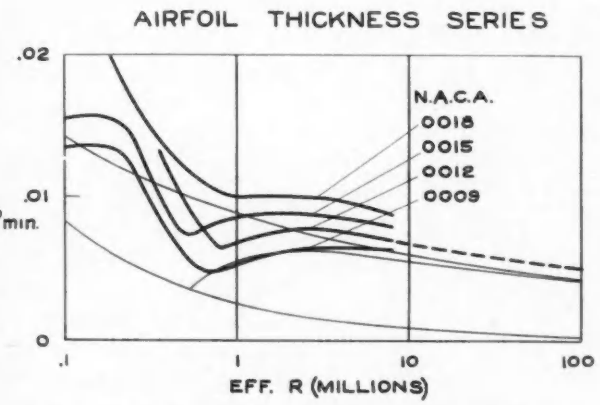


Fig. 9 – Variation of Drag with Reynolds Number for Symmetrical Airfolds of Varying Thickness

serious, because we have no equipment capable of studying the subject experimentally in the higher full-scale range of Reynolds number in which we are at present most interested. Recourse, therefore, must be had to theory.

The theoretical problem has been attacked by means of two methods. According to the first, the laminar boundary layer is supposed to become unstable. Small disturbances that were damped out by the viscous forces at low values of the Reynolds number lose, at high Reynolds numbers, the damping necessary to prevent their growth into turbulence. Many prominent mathematical physicists have attacked this phase of the problem without obtaining very satisfactory results.

According to the second method of attack, the mechanism

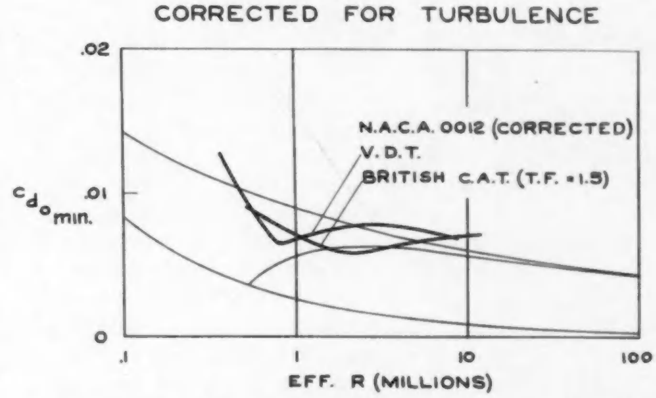


Fig. 10 – N.A.C.A. 0012 Airfoil Minimum Drag As Found from Different Tunnels

of the transition is supposed to be something like that of separation. This comparison has the advantage that the separation phenomenon is comparatively well understood and can be dealt quantitatively with by means of existing theory. The separation referred to may occur only locally, but any return flow tends to cause an accumulation of dead air over which the main flow must run. When a local dead-air region or bump is overrun by the main flow, reduced pressures are created which tend to draw in additional dead air, thus augmenting the disturbance. The turbulence may be considered as the final results of the building up of the bump until its top is carried or curled over by the main overrunning flow and thus moves downstream to form a distinct eddy.

The details of the transition have been observed and photographed at moderate Reynolds numbers on a flat plate in the N.A.C.A. smoke tunnel. When the transition is not brought about prematurely by slight surface roughnesses which also may cause transition by first promoting separation, the normal transition was observed to be closely associated with laminar separation. In general, when the turbulence and roughness were both practically zero, the transition was never observed to occur appreciably forward of the point at which laminar separation normally occurred. Furthermore B. M. Jones at Cambridge reports[4, 5] that he and his associates have found in flight laminar boundary layers on very smooth airplane wings sufficiently extensive to approach the laminar separation region. The fact that such extensive laminar boundary layers are not ordinarily observed at high Reynolds numbers in wind tunnels may be explained as the result of the airstream turbulence. The turbulence tends to produce localized pressure gradients along the airfoil surface that combine with the general pressure gradient to produce local separation and hence, by this theory, also to produce transition at points farther forward than the usual separation point. In fact, this

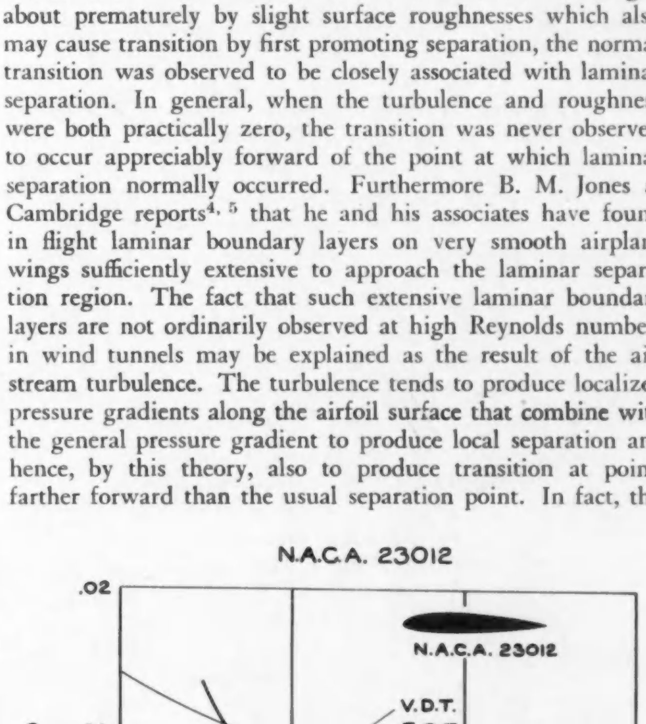


Fig. 11 – N.A.C.A. 23012 Airfoil Minimum Drag As Found from Different Tunnels

[4] See *The Journal of the Royal Aeronautical Society*, May, 1937, pp. 339-356; "Profile Drag," by B. Melvill Jones.

[5] See N.A.C.A. Technical Memorandum No. 751, 1934; "Investigation of Boundary Layers on an Airplane Wing in Free Flight," by J. Stüper.

second method of attack recently has gained much prestige owing to the fact that G. I. Taylor employed equivalent concepts to make quantitative predictions about the results of sphere-drag tests in turbulent wind tunnels.

These concepts may now be extended to account, in a general way, for the difference between the two drag curves in Fig. 10. In the variable-density tunnel, where the pressure gradients associated with the turbulence are relatively large in relation to those along the airfoil surface, they may combine to produce an adverse gradient of sufficient intensity to start local separation, even in the generally favorable gradient field near the airfoil nose. A relatively early and rapid forward movement of the transition point, as indicated by the rising drag curve, is then obtained. In the British compressed-air tunnel, however, where the pressure gradients associated with the turbulence are relatively less, the transition point is more reluctant to pass forward into the generally favorable pressure field; hence the later and less rapid increase of the drag coefficient.

The few points shown in Fig. 11 for the N.A.C.A. 23012 airfoil and obtained from tests in the still less turbulent N.A.C.A. full-scale tunnel show, with increasing Reynolds number, little if any rise in drag that may be attributed to a forward movement of the transition point. On the other hand, the failure of the drag points to fall much above the turbulent skin-friction curve indicates the presence of a rather extensive laminar layer. Otherwise the increased velocities over the airfoil, as compared with the flat plate, and the pressure drag would cause the airfoil drag to be considerably higher. This result may be associated with the theory that the forward movement of the transition point is caused by local pressure gradients associated with the tunnel turbulence, so that its movement is very slow when the turbulence is small; at least this theory seems tenable for smooth airfoils in the lower full-scale range. Now consider an extension of the same theory.

If the turbulence is zero, as it sometimes is in free air, the theory, carried to its logical conclusion, seems to indicate that the transition point will not move forward toward the leading edge of the airfoil as it does in the wind tunnel. If this supposition is true and other disturbances, such as turbulence originating near the nose or due to surface roughness, do not alter the situation, such a conclusion has considerable practical significance. A practical result is indicated in Fig. 12 by the dotted line showing how extrapolations should be made on this basis. The rise in drag associated with the forward movement of the transition point is assumed not to occur in free air at zero turbulence, the transition point remaining near the laminar separation point. It is then noted that the drag reaches a surprisingly low figure at a Reynolds number of 100,000,000.

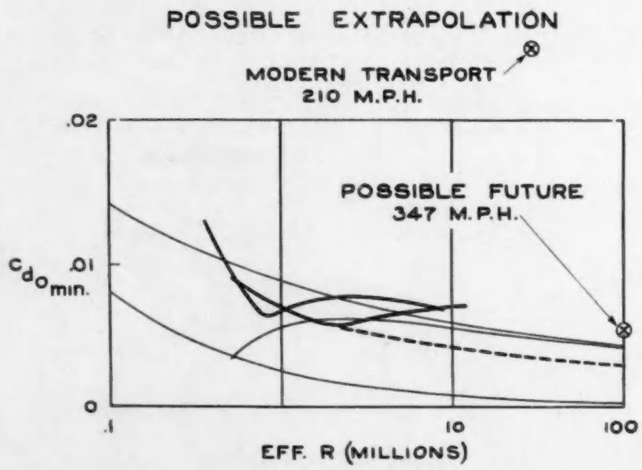


Fig. 12 – Possible Extrapolation of Tunnel Test Data into the Higher Full-Scale Range of the Reynolds Number

The importance of this possible result is further brought out by the comparison shown in Fig. 12 between two airplanes. The upper point ($C_D = 0.0246$) represents a conventional modern transport airplane having a speed of 210 m.p.h. The lower point represents a large hypothetical airplane having the same power and wing loading but designed to have very smooth surfaces, pusher propellers, and the other requirements necessary in order to take full advantage of the possible laminar flows over its forward surfaces. The combined wing, fuselage, interference, and tail-surface drag is based on actual tests of complete models in the variable-density tunnel but the extrapolation to 100,000,000 is based on the assumption that laminar boundary layers on the forward portions of the surfaces may be realized. The comparison is shown primarily to indicate that there is no necessity for pessimism concerning possible future aerodynamic improvement. Incidentally, even further drag reductions may be possible. For example, most of the fuselage and part of the tail-surface drag might have been eliminated by using the flying wing; furthermore, the possibilities of boundary-layer control have not even been considered. Nevertheless, the possible drag reductions considered allow a speed increase from 210 to 347 m.p.h.

The final conclusion, however, is that we do not know whether or not such gains are possible, but it is evident that the possible gains are large enough to justify immediate and careful investigation. Unfortunately, the necessary investigations require equipment that is not available. The present knowledge of wind tunnels makes it appear feasible to construct suitable equipment giving an air stream of effectively zero turbulence and capable of reaching the very large Reynolds numbers for which engineers will very soon require reliable data.

The Throttle-Stop in Light Fleet Units

THERE is one item of which I have not spoken heretofore but which, to my mind, has been of such importance that I want to take the time to make special mention of it. I am referring to that little gadget known as the throttle-stop and I take a personal pride in the fact that our organization had a part in its development. The average fleet owner does not need the performance and top speed which is being built into the light automobiles of today. Economy of operation is far more desirable for our purposes, and you know that economy and performance do not travel together. We experimented with stopping our throttle at a point where it was only about one-third open, at which point the cars had a top speed of from 55 to 60 m.p.h. This we considered a sufficient rate for business purposes. The car was a little slower in acceleration and had to go into gear on climbing some hills, but it did have economy of operation. There was some growling from the drivers, as they are only human and, even as you and I, would like to have the best, be it in performance, speed, or appearance, but that growling disappeared when drivers were educated to the necessity for economy.

We formerly made our own throttle-stops and did our own work on the engines, but today we can all buy "economy models" with throttle-stops built into the car by the manufacturer.

Excerpt from the paper: "Executive Control of Public Utility Fleet Operations," by F. B. Flahive, presented at the Transportation and Maintenance Regional Meeting of the Society on Public Utility Fleet Operation, Baltimore, Md., April 16, 1937.

Features of the In-Line Air-Cooled Aircraft Engine

By A. T. Gregory
Ranger Engineering Corp.

WITH engine outputs continually going up it is worthy to note that the in-line air-cooled engine possesses certain inherent characteristics which make it particularly suitable as an aircraft engine of high output.

Satisfactory cooling of this type of engine has been obtained at higher rated specific outputs than have yet been achieved in any other kind of air-cooled engine.

A type of valve gear can be used which, in addition to being suitable for high-speed operation, permits long periods of operation without the necessity for checking valve clearances.

The lubrication of this type of engine appears to be less of a problem than that of the slower speed radials.

Smoothness of operation and relative quietness at high speed not only afford comfort to pilots and passengers, but also affect favorably the life of both engine and airplane.

The cowling of the in-line engine is relatively simple and permits excellent visibility, combined with the possibility of reduced drag.

Specific weights of in-line engines compare favorably with other engines of equal horsepower. As specific outputs are increased, the in-line engine should gain a weight advantage over other types.

THE in-line air-cooled engine has been shown in recent years to be readily adaptable to a number of engine forms and arrangements. Current engines include inverted line and V-types, horizontal-opposed and H-type engines. Numbers of cylinders per engine vary from 4 to 24, whereas engine speeds range from around 2000 r.p.m. to 4000 r.p.m. In view of this versatility of design and the intense general interest in aircraft-engine development at the present time, it seems pertinent to discuss some of the characteristic features of the line type of engine.

Briefly, the in-line air-cooled engine is an engine that is supposed to cool perfectly even though the front cylinder shuts off the cooling air from the rest of the cylinders. Its frontal area is small so that it should fit into almost any fuselage without increasing the frontal area. It should allow perfect visibility and have a high thrust line. In the higher horsepowers particularly the line engine should be lighter than other types of engine and should require comparatively little servicing.

Engine Cooling

The cooling of a line engine involves the building up of pressure on one side of the cylinder bank and the creation of suction on the other side. In this way a cross-flow is induced, causing the air to flow around the cylinders. Fig. 1 shows a conventional arrangement for cooling a six-cylinder engine. Air enters the scoop at *a* and, after circulating around the cylinders, leaves the engine compartment *c* through the louvre at *b*. Arrows indicate the direction of the cooling-air flow. The air is constrained to flow around the rear or low-pressure side of the cylinders by baffles as shown.

Some of the first attempts to cool a line engine resulted surprisingly in the rear cylinders being very well cooled, while the front cylinders were scarcely cooled at all. When baffles were placed on the outside of the cylinder bank, a higher pressure was built up in the scoop and the cooling of the various cylinders became more equalized. Still, for high-output engines the results were not altogether satisfactory.

In analyzing this problem, it appears that the probable reason for the improved cooling at the rear of the engine is that air entering the scoop has a high velocity and therefore a relatively low static pressure. There is not much pressure head at the front of the engine, therefore, to cause the air to turn and flow across the engine. At the rear of the scoop all of the air is stopped and its velocity head is converted into pressure head. Consequently, there is a large pressure drop across the cylinders at the rear of the engine causing a large flow of air over the rear cylinders.

It is evident that, to obtain equalized cooling on all cylinders, it is essential to obtain equal pressure over the full length of the engine. This result might be achieved if the velocity head of the incoming air could be converted into pressure head as soon as the air enters the scoop. With propeller blades passing across the air-scoop opening at high velocity, however, the problem of eliminating air currents inside the scoop is not simple. Furthermore, not only the velocity, but also the direction of flow of the air as it enters

[This paper was presented at the Semi-Annual Meeting of the Society, White Sulphur Springs, West Va., May 5, 1937.]

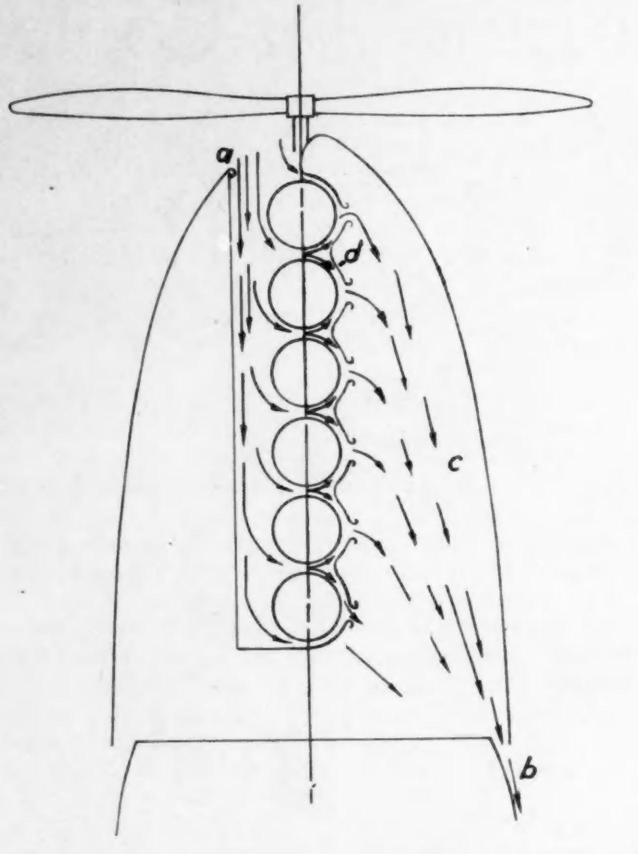


Fig. 1 – Conventional Arrangement for Cooling Six-Cylinder Air-Cooled Line Engine

the scoop affects the engine cooling. When motoring-over a six-cylinder engine on the ground, the front cylinders usually cool better because of getting a direct air blast from the propeller, while the rear cylinders tend to overheat. During flight, however, the rear cylinders cool well and the front cylinders run hot. A satisfactory cooling system, therefore, must be capable of equalizing the pressure throughout the scoop under all operating conditions.

In Fig. 2 are shown diagrammatically the three general types of air scoop which have been used. The type shown at *A* is the usual straight scoop, which gives quite satisfactory results. In the scoop at *B*, however, an attempt was made to reduce the velocity of the air after it entered the scoop by increasing the cross-sectional area of the scoop toward the rear of the engine. Although air pressures may be somewhat more equalized in this type of scoop, eddy currents set up by the propeller blades can still disturb the air flow over the various cylinders and prevent uniform cooling.

In the scoop shown at *C* the cross-sectional area of the scoop decreases from front to rear. The air in this type of scoop is not all stopped at the rear wall of the scoop. The large part of the air is stopped as it strikes the sloping wall of the scoop. This design should produce uniform pressure along the cylinder bank and be less affected by gusts or air currents from the propeller.

In general, it may be said that the higher the pressure within the scoop, the more uniformly will be the pressure distribution over the length of the engine and, therefore, the more uniform will be the cooling of the various cylinders. This condition means that the engine must be completely baffled and all possible leakages from the scoop stopped up. The scoop opening should be located at a point of high pressure on the cowl and generally as far below the propeller shaft as possible.

It is well known that certain portions of the cylinder run hotter than others. This condition is true of the line engine as well as of the radial. Between cylinders the fin heights must be cut down so as not to lengthen the engine unduly, and spark-plugs must be located just at those points where the fins are reduced.

Successful cooling of any design of cylinder under maximum performance conditions involves three steps: First, the cylinder must be provided with adequate fin surfaces properly designed for the air-flow conditions to be obtained. Second, the cooling system must be laid out for obtaining as large a pressure drop as possible across the cylinders. Third, means must be provided to obtain the necessary control of direction and velocity of the cooling air so as to cool the hottest portions of the engine more effectively.

Much has been written on the design of cooling fins and no more need be added here, except possibly to refer to Roland Chilton's excellent paper on this subject.[1] Although Mr. Chilton was concerned primarily with radial-engine cylinders, the principles which he outlines are equally applicable to the line-engine cylinder.

The general features of the cooling system for the line engine have been discussed in connection with Figs. 1 and 2. Considerable work still remains to be done to determine the optimum locations, size, and shape of the cowl openings in order to obtain the maximum possible pressure drop.

There remains, then, for consideration the means by which the cooling air flow can be controlled so as to improve the cooling of a given engine. Such means have been worked out for the line engine and they consist in providing complete air-jacketing on the engine.

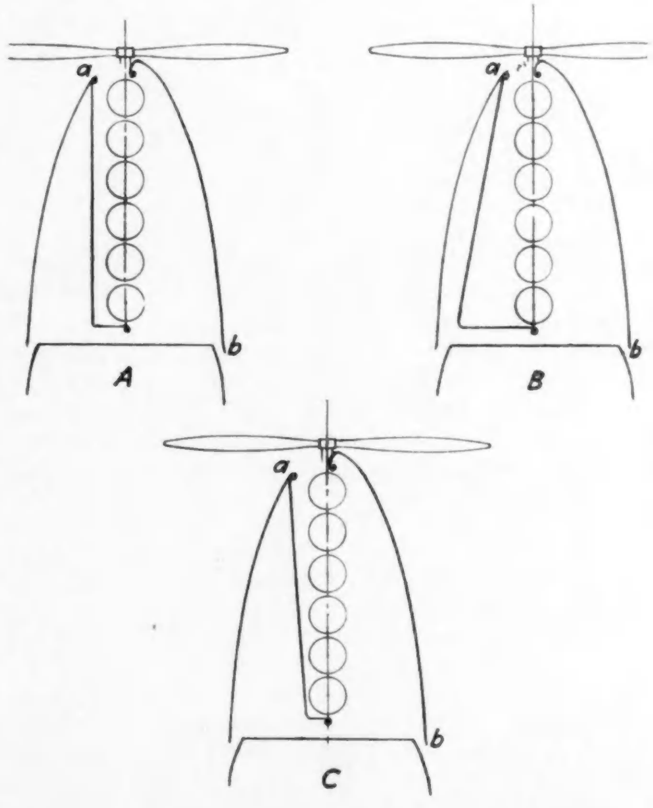


Fig. 2 – Three Types of Air Scoop Used for Cooling Line Engines

[1] See S.A.E. TRANSACTIONS, September, 1931, pp. 542-545; "Air-Cooled Cylinder-Head Design," by Roland Chilton.

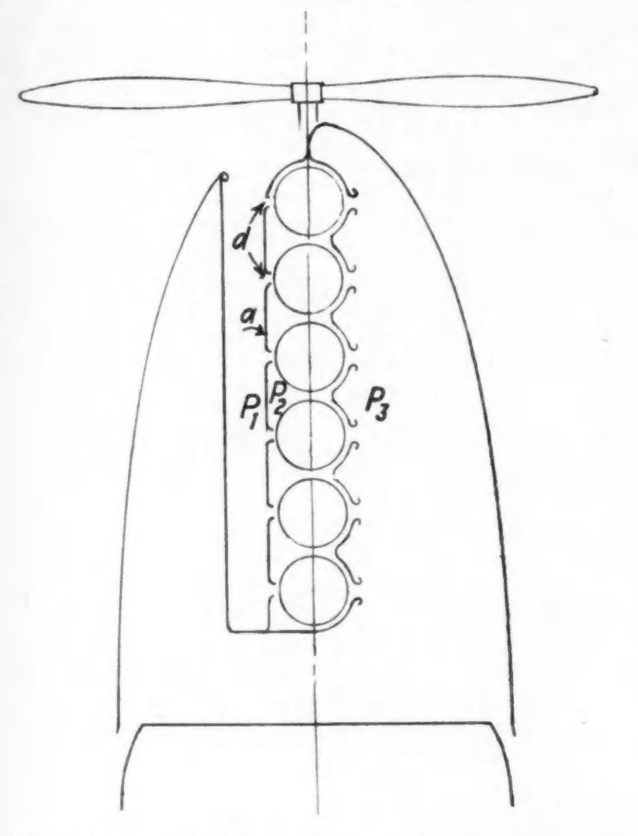


Fig. 3 – Arrangement Providing Complete Air-Jacketing on Air-Cooled Line Engine

The air-jacketing of the line engine is a rather simple matter. With rear or outside baffles bearing tightly against the fins, one half of the jacket is finished. It is necessary only to place a plate along the cylinder bank on the high-pressure side to complete the jacket. This plate, then, separates the cylinders from the cooling air in the scoop, as shown at *a* in Fig. 3. Slots or orifices *d* in the plate admit air into the jacket, which has an intermediate pressure, P_2, between the scoop pressure, P_1, and the pressure, P_3, on the outside of the engine.

The most important duty of the orifice plate is to cause a large proportion of the cooling air to strike the cylinders first at the hottest points at a relatively high velocity. These points, then, will be cooled more effectively than with air flowing over them at low velocity, which is the condition obtained without the orifice plate. Other parts of the cylinder not requiring such intense cooling are supplied with a certain amount of cooling air metered through the slots, *d*, on the cylinder centerlines.

Fig. 4 shows the complete air jacket on the engine and illustrates how the desired air-flow conditions are obtained for cooling the spark-plugs and the areas adjacent to the spark-plug bosses. As will be seen, the incoming air is caused to impinge directly against the spark-plugs and adjacent portions of the cylinders. After passing over the cylinders the major portion of the air leaves the jacket through the spark-plug hole in the rear baffles. The rear baffles are not only clamped tightly against the cylinder fins so as to wrap the air around the cylinders, but these baffles block up the entire space between each pair of cylinders. Thus, all of the air is constrained to flow out either from between the fins or over the rear spark-plugs and adjacent cylinder walls.

The outstanding advantage of using complete air-jacketing is the degree of control which it gives. The rate of flow of air through the orifice plate into the air jacket is governed by the pressure differential between the scoop and the jacket. Likewise, the rate of flow out of the jacket through the rear baffles depends upon the pressure drop between the jacket and the outside of the engine. Each of the pressure differentials can be controlled by the sizes of the openings both in the orifice plate and in and between the rear baffles. If one cylinder does not cool quite as well as the others, some slight modification in the shape of the jacket or in the size of the openings usually will suffice to overcome the trouble.

An additional advantage from the use of air jackets is the fact that more uniform pressure is obtained over the length of the engine. Cooling air flow is more restricted so that a smaller quantity of air performs the cooling. Thus, the cooling is more uniform while, at the same time, the drag is affected favorably.

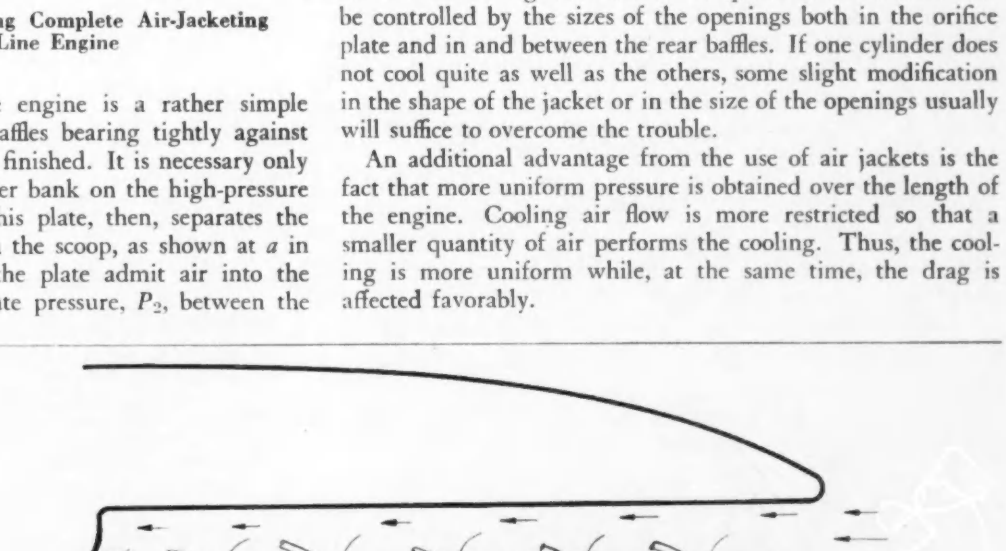


Fig. 4– Completely Air-Jacketed Line Engine Showing Air-Flow Conditions Around Spark-Plugs and Over the Cylinder Heads

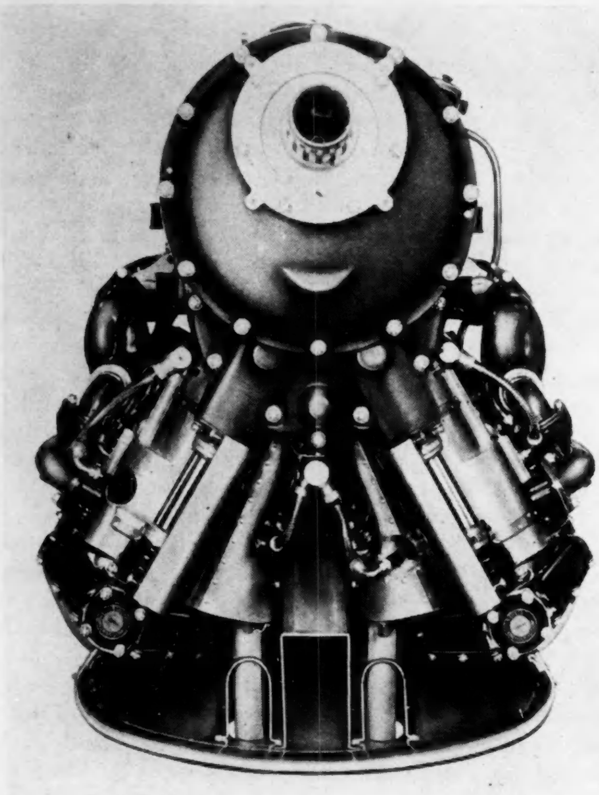


Fig. 5 – 420-Hp. Ranger SGV-770 Engine with Air Jackets in Place

Fig. 5 shows a 420-hp. Ranger SGV-770 engine with the air jackets in place. It will be observed that the cylinders are covered completely, leaving no exposed fins. Cooling air enters the vee between the two banks of cylinders. This air is trapped by the scoop which is closed at the rear by a back plate. The air then enters the jackets through the spark-plug holes in the plates, which are clearly shown. A small narrow slot is provided on each cylinder centerline to allow additional cooling air to flow to the barrels. Some air leaks into the jacket under the bottom edge of the plates which could not be closed up tightly. Along this edge the plates were made to fit the cylinders as tightly as possible. Between the bottom and top of the plates, however, they do not fit tightly against the cylinders, but allow free flow of air within the jackets. In this way a uniform pressure is maintained on all cylinders.

One of the exit holes at the spark-plugs is shown in the baffle on one side of the engine. It will be seen that the air is constrained by the baffles to flow around the rear of the cylinders. The curled-up lip on the baffles has been found to facilitate greatly the flow of cooling air through them. The air duct shown at the center of the scoop is for conducting cold air to the carburetor. Shields shown around the exhaust stacks are used to reduce radiation to the cooling air before it strikes the cylinders.

The spark-plug holes in both plates and baffles are large enough to permit removal of the spark-plugs without disturbing either plates or baffles. The total area available for the flow of air into the jackets, including the leakage area previously mentioned, is 110 sq. in. on this engine, which amounts to 0.26 sq. in. per hp. The total area available for the flow of air out of the jackets is 125 sq. in. or 0.30 sq. in. per hp. When operated under rated conditions of power and speed, the temperature rise across the cylinders is approximately 80 deg. fahr. The pressure drop across the orifice plates is about 45 per cent of the total pressure drop across the cylinders.

It has been found possible to control the cooling by means of the air jackets so that the temperatures of all 24 spark-plugs in a V-12 engine are held within a 100 deg. fahr. range with the engine running under severe operating conditions. Test results show that spark-plug temperatures were lowered by more than 50 deg. fahr. by the installation of the air jackets. Although barrel temperatures were raised slightly, they still remained relatively cool after installation of the jackets. On the original test of the air jackets, no slots were made in the plates to permit cooling air to reach the barrels. The only air reaching the barrels flowed upward from the spark-plug holes. The engine was run to within 65 per cent of rated power on propeller load before overheating occurred on the barrels. A ¼-in. slot was then made along each cylinder barrel, after which no further difficulty was experienced in cooling the barrels.

The cylinder used on this engine is shown in Fig. 6. The height of the fins on the flattened side of the cylinder will be seen to be relatively small, so that the amount of cooling surface available for cooling the spark-plug is small. This condition has been helped by providing additional fins with closer spacing at this point and by the use of the type of spark-plug shown in Fig. 7. This is a short-reach plug having a number of cooling fins on the shell, which has been extended for some distance above the threads. Cooling of the center electrode has also been improved on this plug by the greater length of bearing between the center electrode and the outer shell.

In supercharged V-12 engines with cooling air entering the vee it is sometimes thought desirable to place the intake manifolds within the vee and exhaust from the outside of the engine. In this way some intercooling would be obtained

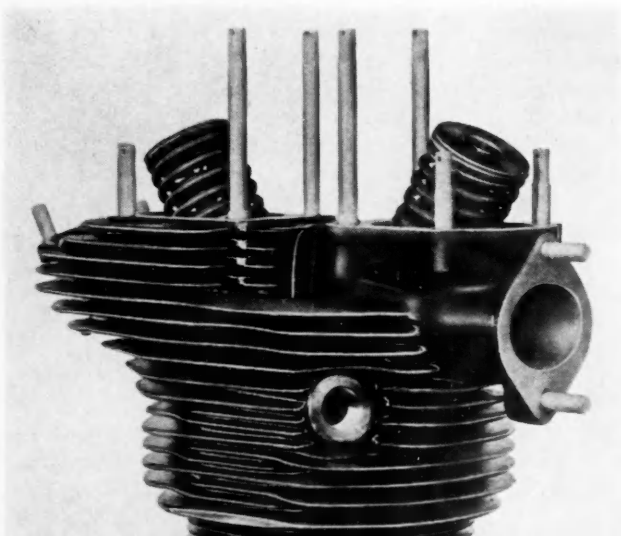


Fig. 6 – Ranger Engine Cylinder Assembly

from the ordinary induction system. With a controlled cooling system such as is obtained with complete air-jacketing, it should be possible to obtain satisfactory cooling with such an engine arrangement.

In naturally aspirated engines, however, it does not appear desirable to arrange the intake manifolds within the vee. It is probably advantageous to have the manifolds heated by the cooling air as it leaves the cylinders and therefore to arrange them on the outside of the engine. The heated manifolds provide improved distribution to the various cylinders and thus raise the power output somewhat. Complete air-jacketing is hardly necessary on this type of engine.

Installation of a Line Engine

The installation of a line engine in an airplane illustrates some characteristic features of this type of engine. Fig. 8 shows an installation of a Ranger 420-hp. inverted V-type engine in a Fairchild "82" airplane. The engine is completely air-jacketed, this installation being the first to be made of an air-jacketed engine. Originally this engine was rated at 420 hp. at sea level on 87-octane fuel. The installation of air jackets, however, made it possible to obtain an altitude rating of 420 hp. at 3000 ft. on 80-octane fuel. It is significant that at rated power the specific output of the engine is 0.54 hp. per cu. inch.

Fig. 7 – Finned Spark-Plug

The opening in the nose cowl for the cooling air is clearly shown in the figure. Some of the air entering this opening goes to the carburetor as previously indicated, while part of it is used for cooling the oil tank. The carburetor air duct cannot be seen, but the air duct for conducting cooling air to the shroud around the oil tank is shown just behind the propeller blade. The net area of the cowl opening available for cooling air to the cylinders is a little less than 200 sq. in., or approximately 22 per cent of the frontal area of the nose cowl. This area corresponds to slightly under 0.5 sq. in. per hp. No attempt has been made to reduce this area although it is planned to use a shutter in cold weather.

In this installation the exhaust stacks are carried straight downward and then are curved to the rear to enter the collectors at an angle of about 45 deg. Inside each collector is a duct, open at the front for taking in cold air. One of these ducts leads to the cabin for cabin heating, whereas the other is led to the shroud around the oil tank. A three-way valve is used to control the heat to the tank. Either heated air from the exhaust collector or cold air from the front of the cowl can be admitted to the shroud.

A unique arrangement is used for heating the air to the carburetor. Cold air passes upward over the exhaust collectors into two narrow vertical passages containing the exhaust stacks from the front four cylinders on each bank. At

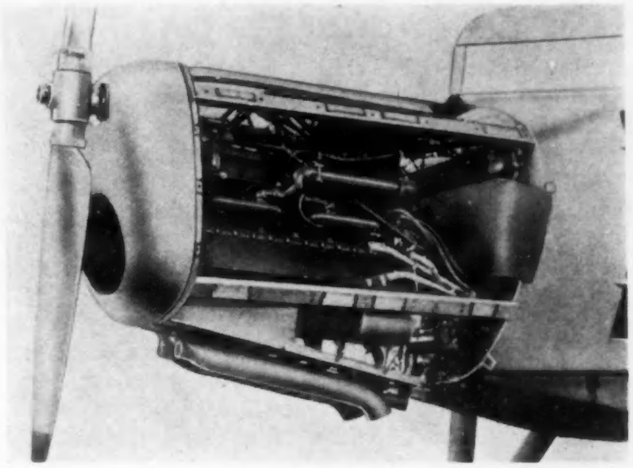


Fig. 8 – Ranger SGV-770 Installation in Fairchild 82 Airplane

a point close to the engine these passages connect with ducts leading to the carburetor elbow at the rear of the engine. Before reaching the elbow the air is constrained to flow over two more exhaust stacks from the two rear cylinders. Thus, the air is heated by means of the six pairs of exhaust stacks as well as by the collector. A valve in the carburetor elbow is used for controlling the amount of heat to the carburetor air. This system has been found to have a heating capacity sufficient to raise the carburetor air temperature 40 deg. fahr. Additional heating capacity could be provided by corrugating pipes and by altering the air passages so as to cause the air to flow in more intimate contact with the hot surfaces. It will be observed that this type of carburetor air heater is particularly advantageous for stormy weather conditions, since the air must flow upward to enter the carburetor air duct.

It should be pointed out here that, from an installation standpoint, the use of an updraft carburetor appears to be a distinct advantage for the inverted V-type of engine. Both hot and cold air ducts can be arranged conveniently to the carburetor, whereas the air can be taken in at points giving good ram both in level flight and in climb.

The breakdown weight analysis of the installation, which is contained in Table 1, gives an idea of what can be done with the line engine. It will be noted that the specific weight of the installed engine, based on rated horsepower, is 2.25 lb. per hp., which compares pretty well with radial engine practice. The weights of the engine mount and exhaust manifolds are somewhat heavier than those for the radial engine in this same airplane. The combined weights of the cooling air scoop and cowl on the line engine, however, are considerably lighter

Table 1 – Weight Analysis of Ranger SGV-770 Engine Installation

	Weight, lb.
Propeller	102.0
Engine	635.0
Starter	32.0
Generator (with control box)	16.8
Exhaust manifolds	26.0
Carburetor heater and air scoop	18.0
Engine cowl	65.0
Engine mount	28.0
Oil cooler	16.0
Oil & gas lines & connections	8.0
Total	946.8

Specific weight of installed engine, $\frac{946.8}{420} = 2.25$ lb. per hp.

than the cowling used on the radial engine. The complete installed weight of the engine is approximately 125 lb. lighter than that of the radial engine with the same equipment, due primarily to the fact that the radial engine is considerably heavier.

Fig. 9 shows a side view of the airplane and gives some idea of the clean appearance of the cowling with the line engine. Excellent visibility has been provided while, at the same time, a high thrust line is obtained. Gross weight of the plane, which is used as a freight carrier, is 6300 lb., and top speed is 145 m.p.h.

The cooling in a plane of this speed has been very satisfactory. Operation at full throttle at 3000 ft. with 3 in. of water pressure drop across the cylinders and 50 deg. fahr. cooling air temperature shows maximum cylinder-head temperatures of 450 deg. fahr. and maximum barrel temperatures of 225 deg. fahr. Apparently the cooling of the barrels could be cut down somewhat in this installation, which would result in a lowering of the head temperatures, thus bringing them into a more desirable relationship with barrel temperatures.

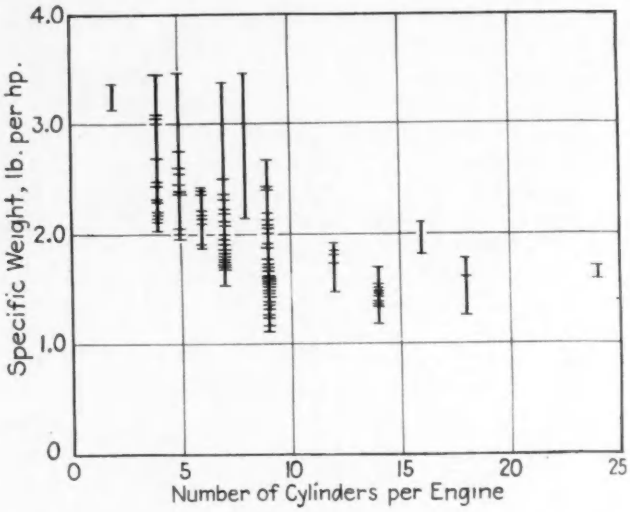


Fig. 10 – Graph of Engine Specific Weight in Lb. per Hp. for Engines Having Various Numbers of Cylinders

Engine Weight

Since the specific weight of an engine in pounds per horsepower is one of the principal factors governing its choice for a particular installation, this factor may be investigated to determine the suitability of the in-line air-cooled type of engine generally for aircraft purposes. Such an investigation would not be complete, however, without proper consideration of the possibilities of developing the line engine for higher outputs and lower specific weights.

In Fig. 10 a graph is shown of engine specific weight in pounds per horsepower for air-cooled engines of various numbers of cylinders. In this graph ordinates represent specific weight, while abscissae give the number of cylinders per engine. Radial engines are represented by those of 5, 7, 9, 14, and 18 cylinders, while line engines are those having 4, 6, 8, 12, 16, and 24 cylinders. The specific weight used in the graph is based upon maximum rated power since this power was thought to be the more reliable indication of the structural durability of an engine. The data shown were taken from a list of current American and European engine specifications[2], each cross in the graph representing an engine.

In view of the fact that the engines represented have not all reached the same degree of development, only general conclusions can be drawn from such a graph. Those types of engine which are the most common, such as the 7-, 9-, and 14-cylinder radials, give fairly reliable indications of average weight per horsepower attainable with those types at the present time. On the other hand, those types of which only a few models have been built, probably show a somewhat higher average weight than they should by comparison, because of having had less development. In spite of these differences in degree of development of various engine types, however, the graph indicates a definite trend toward lower specific weight as the number of cylinders per engine is increased. Further than that, the trend appears to be quite independent of cylinder arrangement. No one type of engine stands out as being particularly superior in regard to specific weight. Average specific weight seems to approach a value of about 1.25 lb. per hp. for engines of the larger number of cylinders, which may mean that some models will weigh about 1.0 lb. per hp.

If the same engines are compared on the basis of specific output in horsepower per cubic inch of piston displacement, the graph shown in Fig. 11 is obtained. In this graph ordinates represent horsepower per cubic inch, whereas abscissae again give the number of cylinders per engine. Horsepower has been taken as maximum rated horsepower as before. Fig. 11 shows a general trend toward higher specific output as the number of cylinders per engine is increased. Only the 18-cylinder radials appear to be out of line with this development, while the line engines generally appear to have a slight advantage over radials in regard to specific output. The H engines seem to have gone higher than any others up to the present time.

Data contained in this same list of current engines indicate that the high-output engines of each type all develop approximately 0.7 hp. per cu. ft. of piston displacement per min.

[2] See *Automotive Industries*, Feb. 27, 1937, pp. 332-335.

Fig. 9 – Fairchild 82 Airplane with Ranger SGV-770 Engine

Table 2 – Weight Comparison of 9-Cylinder Radial Engine and V-12 Inverted In-Line Air-Cooled Engine

	Weight of			
	Radial		V-12	
Group	in per cent	lb. per hp.	in per cent	lb. per hp.
(1) Crankcases	19.4	0.289	24.1	0.364
(2) Crankshaft, including bearings and counterweights	10.5	0.156	7.7	0.116
(3) Propeller shaft, reduction gears, bearings, and nuts	8.5	0.127	5.3	0.080
(4) Connecting-rods, pistons, rings, knuckle-pins, piston-pins	9.3	0.139	8.6	0.130
(5) Valves, springs, washers, rockers, push rods, tappets	6.6	0.098	5.3	0.080
(6) Intake pipes and manifolds	1.4	0.021	1.9	0.028
(7) Cam assembly, camshafts, housings, vertical drives, gears, rocker-box covers, felts, rocker-arm bolts, push-rod housings	2.5	0.037	9.0	0.136
(8) Cylinders and attaching nuts	28.0	0.417	23.4	0.353
(9) Accessory drives, supercharger impeller, and impeller drive	3.1	0.046	3.4	0.051
(10) Oil pumps and strainers	0.7	0.010	1.9	0.028
(11) Ignition, including spark-plugs, magnetos, wiring, shielding and distributors	4.8	0.071	6.0	0.091
(12) Miscellaneous, including carburetor, baffles, fuel pump, miscellaneous bolts and nuts	5.2	0.079	3.4	0.053
Total	100.0	1.490	100.0	1.510

This performance holds for engines of 6 cylinders as well as for engines of 24 cylinders. There is no apparent tendency to deviate widely from this figure, regardless of crankshaft speed, number of cylinders, or cylinder size. This fact is of particular significance when considering going to engines of very high output. If, for instance, it is desired to build a 2000-hp. engine, such an engine will have a piston displacement of approximately 2860 cu. ft. per min., regardless of the arrangement of the cylinders on the engine. The number of cylinders, cylinder size, and r.p.m. would then have to be worked out to obtain a satisfactory combination giving the required piston displacement. As indicated in Fig. 10, however, the engine probably would be lighter, if built of 24 cylinders than if only 12 or 14 cylinders should be used.

The reasons why an engine with many cylinders should weigh less per horsepower than one with few cylinders are not obvious. Generally the opposite is expected. Additional cylinders require larger crankcases, longer crankshafts and more connecting-rods and pistons. Still, line engines are being built as light in pounds per horsepower as are radials of equal power output and fewer cylinders. Certain parts of the line engine, therefore, must be lighter than those parts performing the corresponding functions in radial engines.

In order to study these basic differences between radial and line engines and thus to determine why very high output line engines probably will weigh less than other types, a comparison was made of the weights of the various parts of the radial and line engines. The two engines chosen for this comparison were thought to represent about the same degree of development. The radial was a 9-cylinder engine of large displacement and rather slow speed, whereas the line engine was a V-12 of relatively small displacement and high speed. Although the radial was an engine of considerably higher horsepower output, the specific weights of the two engines were almost identical. The radial engine weighed 1.49 lb. per hp., whereas the line engine weighed 1.51 lb. per hp. with the same equipment. Both engines developed exactly 0.675 hp. per cu. ft. of piston displacement per min. Both engines were equipped with reduction gearing.

Table 2 shows the results of this weight comparison. Weights of the various engine parts are given in per cent of total engine weight and also in pounds per horsepower. As nearly as possible, similar parts or functions in the two engines are grouped together for comparison.

As was expected, the table shows that crankcases weigh about 26 per cent more in the line engine than in the radial. In the radial they comprise less than one-fifth of the total

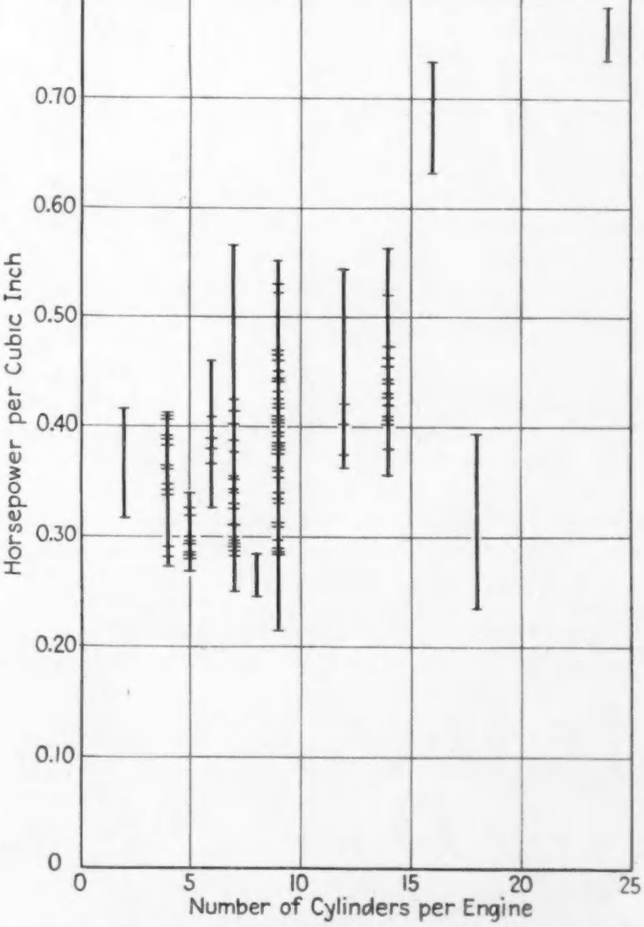


Fig. 11 – Graph of Specific Output in Hp. per Cu. In. for Engines Having Various Numbers of Cylinders

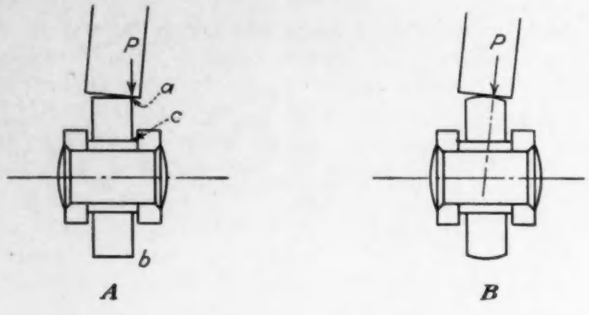


Fig. 12 – Diagram Showing Loading of Bearing in Rocker Roller

A – When Flat-Faced Roller Is Used
B – When Crowned Roller Is Used

engine weight whereas, in the line engine, they amount to nearly one-fourth of total engine weight. On the other hand, crankshaft weight per horsepower is more than 34 per cent greater in the radial than in the line engine. This finding is somewhat of a surprise in view of the greater length of the line engine shaft. The difference is undoubtedly due to the fact that the radial-engine shaft has heavy counterweights and is mounted on heavy roller bearings, whereas the line-engine shaft is not counterweighted and has relatively thin sections. Furthermore, main crankshaft bearings in the line engine are plain bearings, which are relatively light.

The propeller shaft and reduction gears in the radial engine are nearly 60 per cent heavier in pounds per horsepower than in the line engine. Probably the main reason for this difference is the fact that the radial engine uses a planetary type of reduction gear, whereas the line engine has a single pair of herringbone gears.

Connecting rods, pistons, valves, rockers, and so on, on the radial engine account for another 13 per cent greater weight in the radial than in the line engine. This difference is undoubtedly due primarily to the heavier connecting-rod arrangement used on the radial engine. The actual weights of pistons and valves are approximately in the ratio of the cubes of the cylinder diameters. For the same specific output these parts should weigh about the same in pounds per horsepower in the two engines. The differences in their specific weights, therefore, reflect closely the difference in the specific outputs of the two engines. Thus pistons and valves are approximately 38 per cent heavier in the radial engine in pounds per horsepower than in the line engine.

Grouping together Items 2 to 5 of Table 2, it is evident that the main rotating and reciprocating parts in the engine are about one-fourth heavier in the radial engine than in the line engine. This fact is of outstanding importance when considering going to high speeds. Dynamic loads in these parts increase with the square of the speed and engine weight must, therefore, go up accordingly. Thus, in the radial engine one-third of the total engine weight would increase due to this increased loading whereas, in the line engine, only one-fourth of the total weight would be affected. Assuming that both engines are built to about the same factor of safety and that the increase in speed does not involve operation at a critical speed, the weight of the radial engine must go up faster than that of the line engine.

Turning again to Table 2, it will be seen that the intake manifolds on the line engine are somewhat heavier than on the radial, which is to be expected, since they are more complicated in design in order to obtain satisfactory distribution.

Camshafts, camshaft housings, and drives in the line engine are considerably heavier than the cam assembly, drive gears, and so on, employed in the radial. The line engine uses an overhead camshaft, requiring vertical drives and considerable gearing. There will be further discussion of this point a little later.

Cylinder-head and barrel assemblies with their attaching nuts, however, are considerably lighter in the line engine than in the radial. This condition cannot result from a greater proportionate amount of finning on the radial engine cylinder since this cylinder had actually less fin area per cubic inch of displacement than the line-engine cylinder. The difference in cylinder weight per horsepower, therefore, must result primarily from the difference in the specific outputs of the two engines, which amounts to about 38 per cent. Actually, the weights of the individual cylinders on the two engines are in the ratio of the 2.3 powers of their diameters, so that the radial engine could have come out with the same cylinder weight per horsepower with 25 per cent less horsepower per cubic inch. The comparison indicates quite clearly the advantage of going to engines of high specific output.

The fact that the accessory drive group in the radial engine had approximately the same specific weight as in the line engine is rather significant, since, in the line engine the drive is taken through a long flexible shaft from the front of the engine. Oil pumps are heavier in the line engine, since two scavenge pumps are required, both of which are separate from the pressure pump.

The differences shown under ignition weights indicate that the increased weights of spark-plugs, harness, and shielding in the line engine are more than enough to make up for the elimination of one of the magnetos used on the radial. The greater weight of the miscellaneous items in the radial engine cannot be due to the carburetor, since the carburetor on each engine weighs 0.039 lb. per hp. The difference, therefore, must be in baffle weights and other miscellaneous items.

In general, then, the weight analyses show that, although the stationary parts are heavier in the line engine than in the radial, rotating and reciprocating weights are correspondingly lighter. Furthermore, the analyses indicate that increasing the number of cylinders and reducing their size actually may result in reduced cylinder weight per horsepower. It may be significant that the sums of crankcase and cylinder weights per horsepower on both engines are practically identical.

X Engine or H Engine

When 16 or 24 cylinders are to be arranged on an engine, it seems attractive to arrange them in the form of an X rather than an H so as to use a single crankshaft. Thus, the weight of an additional crankshaft would be saved and smaller crankcases would result. If this arrangement is made, however, the connecting-rod and crankshaft arrangement becomes similar to that used in the radial with master connecting-rod and link rods. This type of mechanism has been shown to be relatively heavy, and so is limited to relatively low speeds. For a given horsepower output, then, larger cylinders would be required on the X engine and it is questionable whether the crankcases would be appreciably lighter if at all than on the H engine.

With the light shafts and rods possible in the H engine, high speeds and high specific outputs should be relatively easy to attain, as was indicated earlier in the paper. Cylinder sizes and weights should, therefore, be less than on the X engine, as should also piston and valve weights. Valve gear and accessories should weigh about the same in both engines so that, all in all, the H engine should be the lighter of the two.

Valve Gear

It was shown in Table 2 that camshafts with their drives and housings account for about 9 per cent of total engine weight in the line engine. This figure compares rather unfavorably with the 2.5 per cent for the radial, which is the maximum weight chargeable to those parts performing corresponding functions. The question may be raised, therefore, as to why the line engine should use a type of valve gear that is basically so heavy.

One of the advantages claimed for the line engine with overhead camshaft is that servicing is reduced greatly over customary practice. Valve clearances do not show appreciable change over long periods of operation so that the need for frequent checks is eliminated. With pressure and splash lubrication of valve-gear parts and the almost complete absence of sliding friction between the parts, wear is reduced to a minimum. Not all line engines use overhead camshafts, however, and it may be desirable, therefore, to go into the question of valve-gear design a little more thoroughly at this time.

Because of its inherent balance, the line engine is basically a high-speed engine. The faster it runs, the smoother it runs, so that the wear and tear on the passengers as well as on equipment is spared by going to high speeds. There does not appear to be any particular advantage in rating this type of engine at less than 3000 r.p.m. for very high outputs. Rather, there appear to be decided advantages to be gained from an increase in speed above this value, some of which were indicated in the discussion of engine weight. It is only logical, therefore, that this type of engine should use a valve-gear design suitable for high-speed operation.

Such a valve gear should have the minimum possible reciprocating weight. For, as speed is increased, acceleration loads increase with the square of the speed. When speeds get up into the 3000 to 4000 r.p.m. range, this fact becomes of major importance. Spring sizes go up rapidly to compensate for the increased loading and, as spring sizes go up, spring weight also increases, thus further increasing the reciprocating weight. This process rapidly approaches a point of diminishing returns, until finally increasing the spring strength has little effect upon the valve jumping speed. On the other hand, a reduction in the reciprocating weight of 0.1 lb. would raise the jumping speed by at least 50 r.p.m. The importance, therefore, of starting out with a type of valve gear having the minimum reciprocating weight is readily apparent.

Perhaps the most common type of valve gear used in aircraft engines is the push-rod and rocker type. The reciprocating parts of such a valve gear consist of: valve, with spring retaining washer and springs; rocker arm; push rod; and cam follower. Of the total reciprocating weight represented by these parts, about a third is made up of the push-rod and cam-follower weights. In an engine having a valve jumping speed of 2500 r.p.m., therefore, the elimination of these two parts would raise the jumping speed to around 3000 r.p.m. without any other change. The type of valve gear using an overhead camshaft, therefore, possesses an advantage for high-speed operation in that it eliminates the push-rod and cam follower.

There are, however, two general types of overhead valve gear. In the one the camshaft is located above the valves and the cams bear directly on the ends of the valves whereas, in the other, the valves are operated by rockers actuated by the cams. Although the first of these two types may be the lighter due to the elimination of the rockers, it does not appear to be so well suited for high-speed operation. In the first place there is the manufacturing difficulty involved in producing the parts so that, when finally assembled, the cam bears evenly on the follower over its full width. Added to that is the fact that, at an engine speed of around 4000 r.p.m., the rubbing speed of the cam on the follower would be of the order of 1300 ft. per min. With a load on the cam of some 200 to 300 lb. and the cam making line contact with the follower at best, this design presents a nice lubricating problem. Of course the oil people may come to the rescue with the ideal lubricant, in which case there could be no further objection to this type.

With a valve-gear design using an overhead camshaft and rocker arms, a roller rides on the cam while an adjusting screw bears on the valve. Here the condition of sliding friction between cam and follower is eliminated, but the difficulty of producing a mechanism in which the roller bears uniformly against the cam over its full width is just as acute as in the previous type just discussed. Roller seizure and cam scuffing have been a common experience.

The condition usually obtained because of the necessary manufacturing tolerances is shown exaggerated in Fig. 12 (*A*). All of the load *P* between the cam and roller is seen to be transmitted along the line *a-b* to the roller axis. This condition means that exceedingly high bearing pressures exist at *c*, which break down the oil film and thus cause seizure of the roller on its axis.

The difficulties experienced with roller-sticking have been entirely eliminated by the simple expedient of putting a crown radius on the roller surface. The amount of the crown required depends upon the particular design and the amount of tolerance stack-up. Usually a 2- to 4-in. radius will suffice. Fig. 12 (*B*) shows the condition which is obtained with the use of crowned rollers. With this design the line of action of the force *P* passes through some point nearer to the center of the bearing. It is desirable to have the line of action of the force *P* pass through the middle third of the length of the bearing under all possible conditions of misalignment of roller and cam surfaces. Otherwise, the load is not distributed over the full length of the bearing and excessive pressures result.

Fig. 13 shows a camshaft and a pair of crowned rollers which have been operated together for about 50 hr. at high speed. Both cams and rollers show excellent surfaces. There

Fig. 13 – Camshaft and Crowned Rollers after 50 Hr. of High - Speed Operation

is complete absence of gullies or shoulders formed by the edge of the roller and no evidence of the roller's trying to stick. The roller track is about ⅛ in. wide and is smooth and hard. It may be objected that the effective width of the roller is reduced by putting a crown on it. Such is not the case, however, since with flat-faced rollers the roller rarely bears evenly against the cam over its full width.

Number of Valves per Cylinder

The problem of attaining very high operating speeds with line engines also raises the question of the number of valves to be used per cylinder. The use of four valves instead of two would provide not only better porting with consequent improved volumetric efficiency but also lighter valves and valve gear. A four-valve cylinder would thus make it possible to go to still higher speeds than with the two-valve cylinder.

Preliminary studies indicate that satisfactory gas velocities can be obtained in the ports and valve annulus with the two-valve cylinder at least up to speeds of around 3500 r.p.m. Above that speed some sacrifice may be necessary in altitude rating in order to obtain the desired rated power by means of additional boost. Appreciable curtailment in the altitude rating would not be permissible so that, without going too deeply into the problem, it would appear that there is an upper speed limit around 4000 r.p.m. beyond which it may not be economical to go with the two-valve cylinder.

There are some objections to the four-valve design, the most important of which relates to cooling capacity. It would be difficult to obtain satisfactory finning on the four-valve head. Dead air pockets could hardly be avoided between the valve ports, while the volume of cooling air flow over the cylinder heads undoubtedly would be less than with only two valves. Unless the cylinder size is kept small, or the revolutions per minute are raised to extremely high values, the temperature conditions in the cylinder might create a serious cooling problem, which would make the four-valve design unsuitable for very high horsepowers.

Lubrication

The lubrication of the high-speed engine appears to be less of a problem than that of the slow-speed engine in some respects. The oil is harder to control and seems to find it easier to get by pistons and rings. On the other hand, the oil film on the cylinder walls, being easier to maintain, provides better ring lubrication and thus appears to retard the formation of sludge. Experience indicates that, with the proper amount of a good grade of lubricant, ring-sticking can be avoided in the high-speed, high-output engine.

Several factors contribute to the lubricating conditions found in the high-speed engine. In the first place, the temperature conditions are not nearly so severe as in the slow-speed engine of equal specific output. The heat flow to the cylinder walls per square inch of wall surface per stroke is less than in the slower-speed engines. Thus, the oil on the cylinder surfaces is not heated so highly as in the slow-speed engine and the chances of its lubricating qualities being destroyed by heat are, therefore, less. Furthermore, the shorter length of time available during the expansion stroke for the building up of pressure behind the top rings also results in less oil being scraped off the cylinder walls.

Another factor in maintaining a suitable oil film on the cylinder surfaces is that of piston side pressure. Morris P. Taylor has shown that high piston side pressures result in the piston's squeezing out the oil film and thus raising the friction horsepower[3]. Mr. Taylor showed further that side pressure is primarily a function of gas pressures and is affected only slightly by inertia loads. Piston side pressure in a given engine is, therefore, not appreciably greater at high speeds than at low speeds for the same brake mean effective pressure. At high speeds there is also less time during the stroke to squeeze out the oil film.

[3] See S.A.E. Transactions, May, 1936, pp. 200-205; "The Effect of Gas Pressure on Piston Friction," by Morris P. Taylor.

Discussion

Contends Jacketing Developments Also Apply to Radials

– N. N. Tilley
Continental Motors Corp.

A VERY good case for the in-line air-cooled aircraft engine is made by the development described by Mr. Gregory. It is hoped that the following comments will be considered constructive rather than critical:

The possibilities in the way of small frontal areas together with high crankshaft speeds makes the in-line engine a worthwhile development for aircraft. The development of air jackets as described to give better local control with more uniform and consistent cylinder cooling which results in decrease of required octane value of fuel, should apply equally well to radial as to line engines. To evaluate further improvements in cylinder cooling more data are desired than are presented.

Measurements of mean temperature rise of cooling air and the total weight of cooling air required will enable comparisons of horsepower required for cooling and comparisons of cylinder-cooling losses of high-output air-cooled versus liquid-cooled cylinders. At present the power used for cooling shows up in airplane drag where it is difficult to measure. The heat rejected to the cooling air forms the basis of the amount of air to be handled. Assuming that cylinder-cooling losses are the same for air- and liquid-cooled engines the fan horsepower for power cooling of air-cooled engines can be computed to be as low as 4 per cent of engine power output depending on estimates used for air weight pressure drop and fan efficiency.

Control of cylinder cooling under different conditions of operation becomes an item of considerable importance when the variation of possible operating conditions is considered. If air-cooling has advanced sufficiently to be more than adequate for stall climb of airplanes in hot weather, then it is probable that the cylinders are too cool for cruising level flight in cold weather. Presumably at a later date this feature of installation will be covered fully.

With reference to carburetor air heater work described, it is believed that most of the engine industry has determined that carburetor air intake temperatures must be increased well above 40 deg. fahr. to avoid icing difficulties.

An argument might be started relative to the amount of history between the radial and in-line engine, however, the weight analysis is instructive. It is cause for speculation on a comparison with still more crankshaft speed and more intake manifold pressure for the in-line engine.

The statement that high-output engines all develop approximately 0.7 hp. per cu. ft. piston displacement per min. regardless of size, number of cylinders, or cylinder arrangement is apparently the same as saying that all engines develop the same brake mean effective pressure. This condition may occur for a given octane fuel although data have been presented elsewhere indicating an appreciable variation of brake mean effective pressure with cylinder size, temperature of air-fuel mixture in the intake manifold, and other design factors or operating conditions. If more cylinders make lighter engines, other explanations can be used instead of the argument presented.

Relative to the comparative weight analysis of a radial and line engine, further evaluations than given are desirable on the basis of unit loadings, stresses, and so on. A decreased power-weight ratio is accompanied generally by higher stresses, greater bearing pressures, or higher heat loads somewhere in the engine. Some equalization of these factors is required for a true comparison of engines with different cylinder arrangements.

Practice as shown by current engine specifications does not always insure equalization of such factors.

Regarding lubrication, it is agreed that oil films should be easier to establish at high speed than at low speed, but there are also higher pressures in high-speed engines. If all engines operate at the same brake mean effective pressure, then the cylinder pressure is the same in high-speed as in low-speed engines. In practice there seems to be more difficulty getting engines to operate at speeds in excess of the current values. This difficulty can be due to higher heat loads which cause distortion or more change of dimension than in prior engines. Also oil circulation to cylinders may increase, or prior oil-control provision becomes inadequate, or a new kind of oil needs to be developed. Though theory indicates the path to be followed, a number of trials may be required before the possibilities of the theory can be demonstrated.

Engine and Laboratory Tests of Stability of Aviation Oils[1]

By O. C. Bridgeman[2] and E. W. Aldrich[3]

PURPOSE of the investigation reported in this paper was to find a suitable laboratory test method for the stability of aircraft-engine oils.

Three types of laboratory methods were chosen, and data were obtained on two of them using 22 aviation oils. The two methods were (1) heating the oil with the surface exposed to the air but without aeration, and (2) heating the oil under aerating conditions. Results were compared with engine data on the same 22 oils covering 30 hr. of operation in each case at cruising power with a Pratt & Whitney Hornet engine. Three conclusions are drawn:

(1) Laboratory methods can be developed which will rate the stability of oils in almost any order, depending upon test conditions.

(2) Methods involving aeration of aviation oils are much too severe and do not correlate with engine data.

(3) Heating of aviation oils without aeration at a temperature of approximately 175 deg. cent. appears to be the most significant set of test conditions, and data obtained under these conditions correlate satisfactorily with the service performance of the oils in aviation engines of moderate output.

THE general problem of the stability of lubricating oils for internal-combustion engines is one which thus far does not appear to have been investigated in any comprehensive manner, presumably due to the complexity of the problem and the difficulties of obtaining accurate engine data. A variety of laboratory stability methods, which have more or less significance, have been developed for automobile engine oils, and many of these methods have been used for aviation oils. In most cases, there has been little systematic comparison of the laboratory data with aviation-engine data and, hence, there is little basis for evaluating the significance of the laboratory methods. In commercial practice, the air-lines and engine manufacturers are essentially the testing laboratories of the oil companies and, when an oil is found by them to be satisfactory, it can be purchased and used with reasonable assurance of continued satisfactory engine performance until higher output engines are installed or the severity of operating conditions is increased, at which time evidence of satisfactory stability under the more severe conditions is required. Although this method gives the answer directly in terms of engine performance, it has obvious disadvantages from the standpoint of the time and expense involved when selecting from a group of oils. The availability of a significant laboratory test method would permit the selection of the most stable oil immediately at little expense, or would permit the selection of the two or three most stable oils in the group for confirmation by engine tests. From the standpoint of developing improved oils, and also that of purchasing oils according to specifications, not involving engine tests, a suitable laboratory test method for oil stability is essential.

The term oil stability is used in this paper to indicate the resistance to change of an oil when heated under given conditions either in the engine or in a laboratory apparatus, the resistance to change being measured by the usual tests made on lubricating oil. The present investigation was made to develop a suitable laboratory method for oil stability which would give results significant in terms of the service changes in these oils when used in aviation engines. Since engines vary considerably as regards their operating temperatures particularly on the cylinder walls, and since there is a rather wide variation in severity of operation even with the same engine, provision was made for investigating the effect of temperature on oil stability over wide ranges in the laboratory tests. Three general types of laboratory methods were chosen: (A) heating the oil with the surface exposed to the air but without aeration, (B) heating the oil under aerating conditions, and (C) heating the oil while flowing in a thin film exposed to air down the inside wall of a heated steel cylinder and recirculating the oil at a controlled rate. A large volume of data has been obtained by Methods A and B on 22 aviation oils but preliminary results only have been obtained so far by Method C, and no further details regarding this method will be given at this time. Engine data have been obtained on the 22 oils covering 30 hr. of operation in each case at cruising power with a Pratt & Whitney Hornet engine, Model R1690-32.

[This paper was presented at the National Aeronautic Meeting of the Society, Washington, D. C., March 11, 1937.]

[1] Publication approved by the Director of the National Bureau of Standards of the U. S. Department of Commerce.

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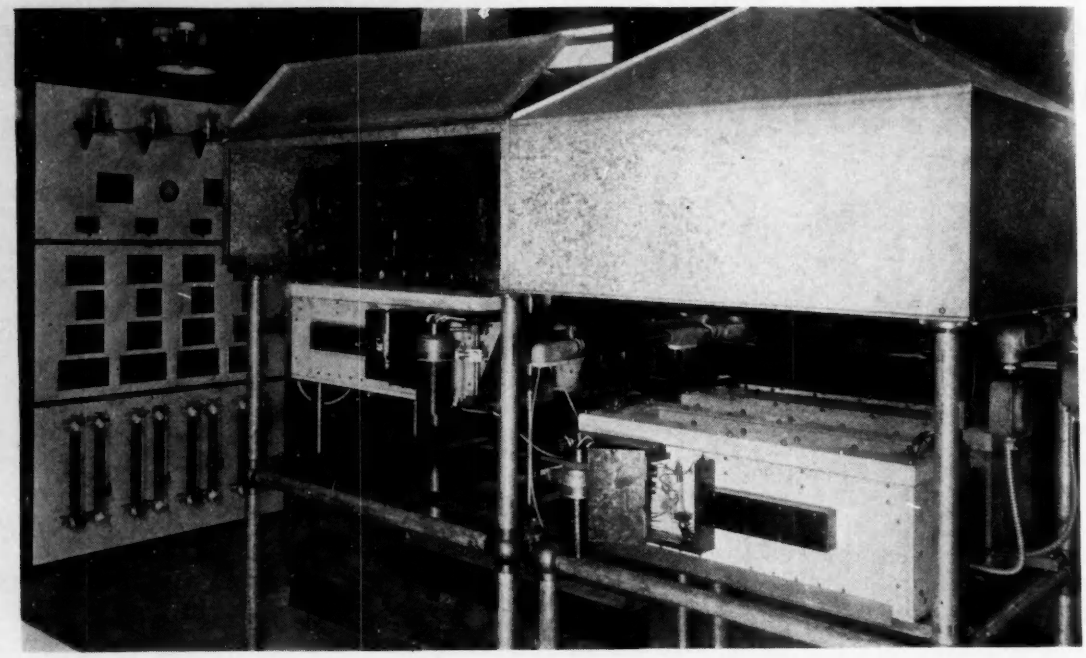

Fig. 1 – Aluminum Blocks for Heating Oil Samples – for Method A on the Right and Method B on the Left

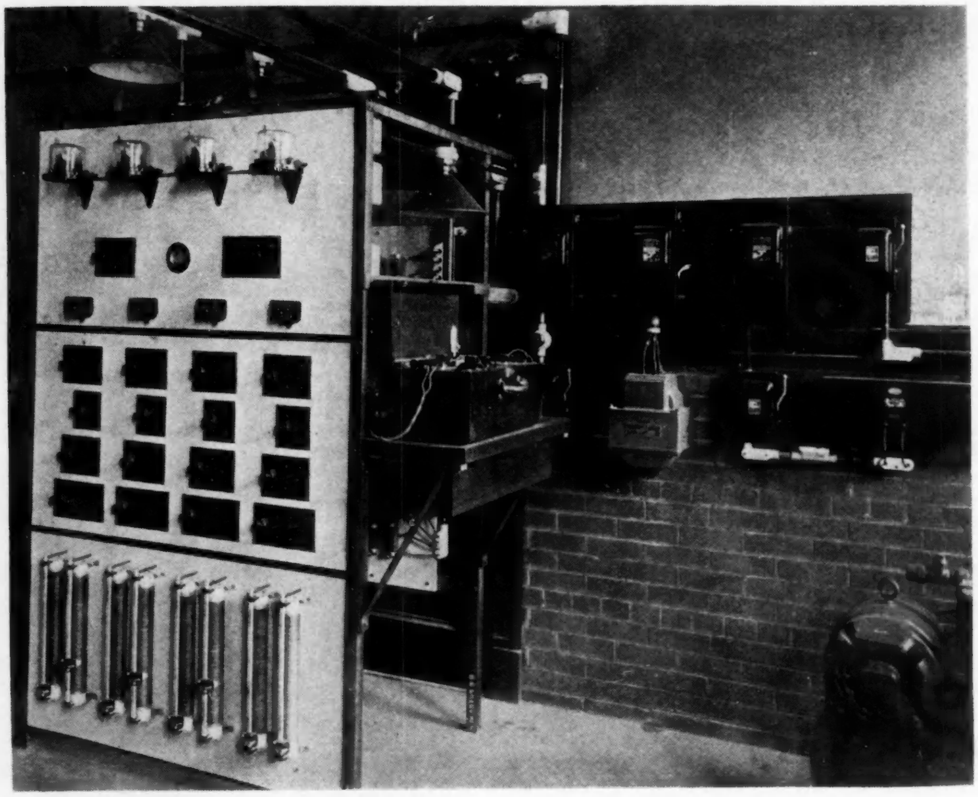

Fig. 2 – Electrical Control Panel for Apparatus Used in both Methods A and B

Description of Laboratory Method A

In order to avoid the use of an oil bath and to eliminate fire hazard, an aluminum block was used for heating the oil samples. This block was 26 in. long, 6 in. wide and 6¼ in. deep, and 6 holes were bored in it to a depth of 4½ in. to receive Pyrex dye-pot beakers of 400-ml. capacity. The block was heated electrically on the bottom and the four sides by means of specially constructed heating elements imbedded in Transite plates and screwed to the aluminum block. The top of the block was covered with a Transite plate having six holes in it of the same diameter as those in the block and, when the beakers were in place, they projected slightly above the top of the plate so that there was free access of air to the surface of the oil in the beakers. A two-arm mercury-in-steel thermo-regulator, inserted in suitable holes in the aluminum block, was used to maintain the oil temperature at any desired value within 0.1 deg. cent. Temperature control was checked by means of three thermocouples inserted in openings spaced along the length of the block. Thermal insulation consisting of 2 in. of rock wool was used on the bottom and four sides and the whole unit was confined in a Transite box open at the top. Two such units were constructed for this work, and are shown at the right-hand side of Fig. 1.

In making a test, 160-gm. oil samples were weighed out in the 400-ml. Pyrex beakers, and these were inserted in the block which had already been brought to the desired tempera-

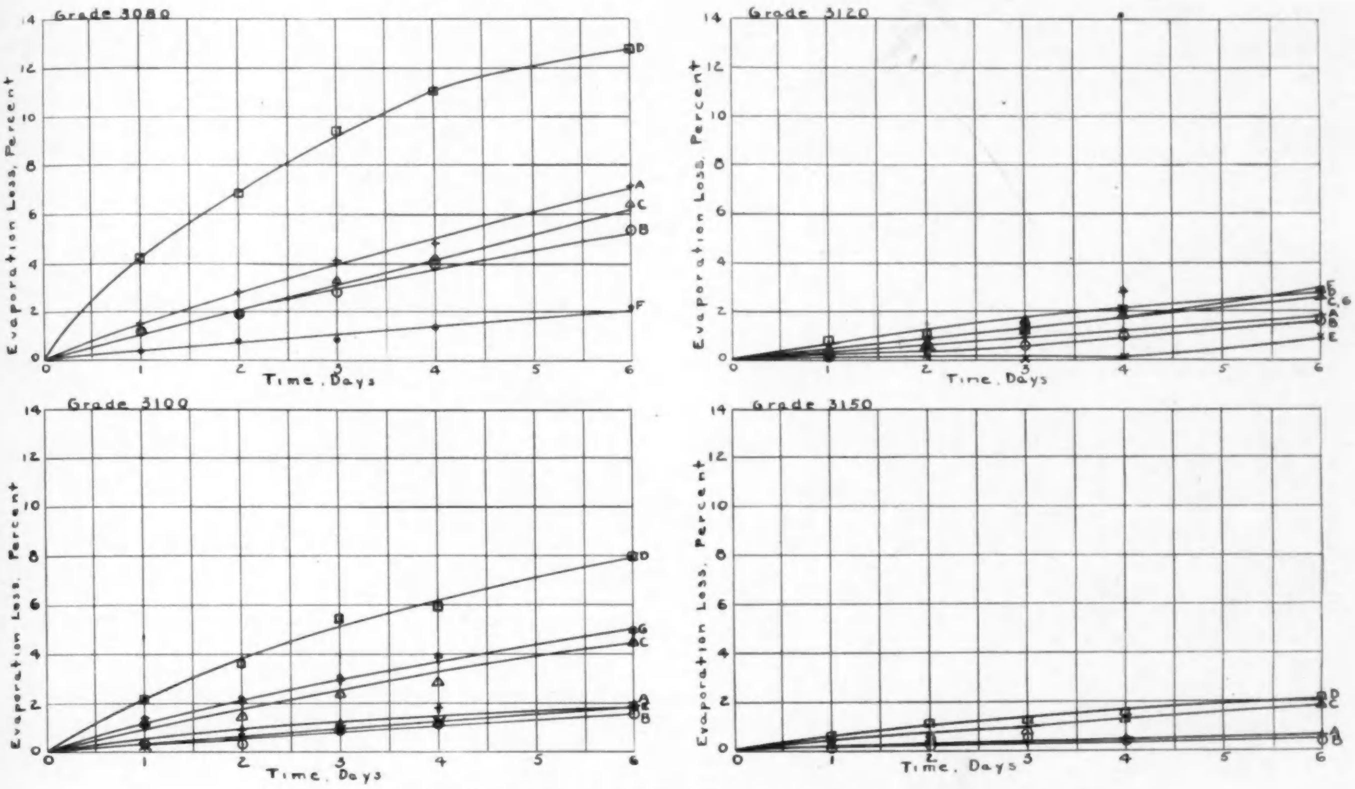

Fig. 3 – Evaporation Loss Data on Aviation Oils by Method A at 175 Deg. Cent.

ture. Additional heat was applied to the block for a few minutes to bring the temperature back to the desired value, and then the samples were allowed to "cook" for the predetermined time. At the end of this period, the 6 beakers were removed and allowed to cool. They were then weighed, so as to determine the evaporation loss, and finally the samples were tested for viscosity, carbon residue, neutralization number, and naphtha insoluble.

Separate runs were made on 22 aviation oils for 1-, 2-, 3-, 4- and 6-day periods at each of the oil temperatures 150, 175, 200, and 225 deg. cent., a day constituting 24 hr. of continuous heating.

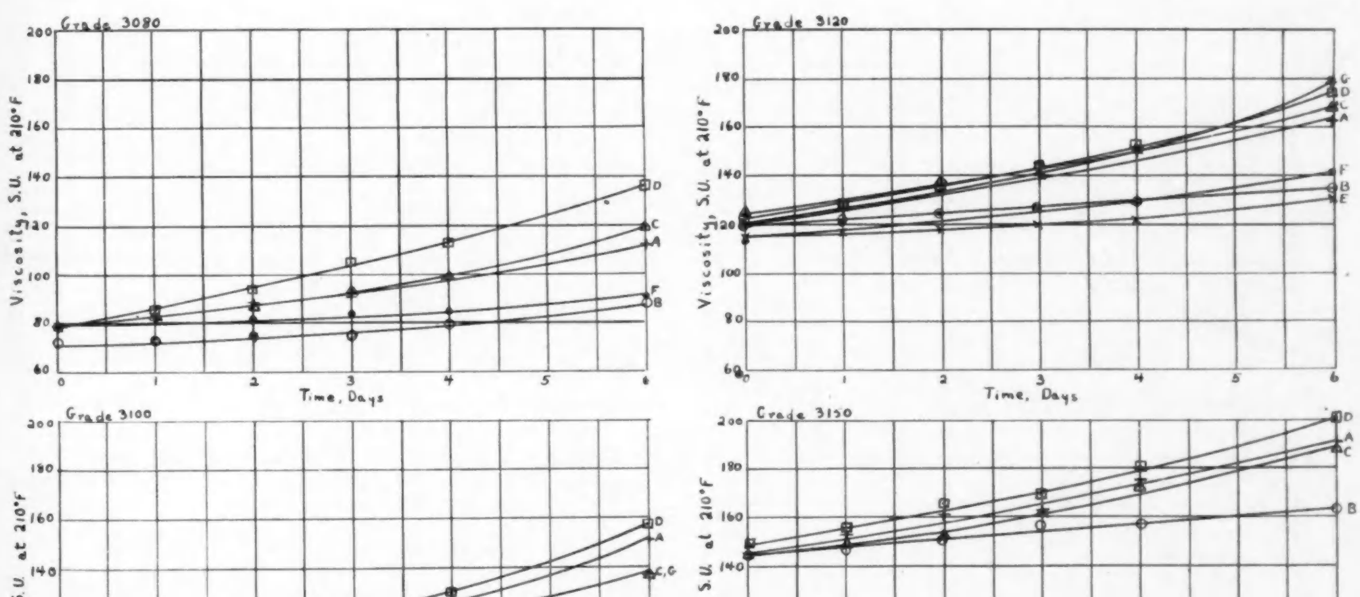

Fig. 4 – Change in Viscosity of Aviation Oils on Heating at 175 Deg. Cent. by Method A

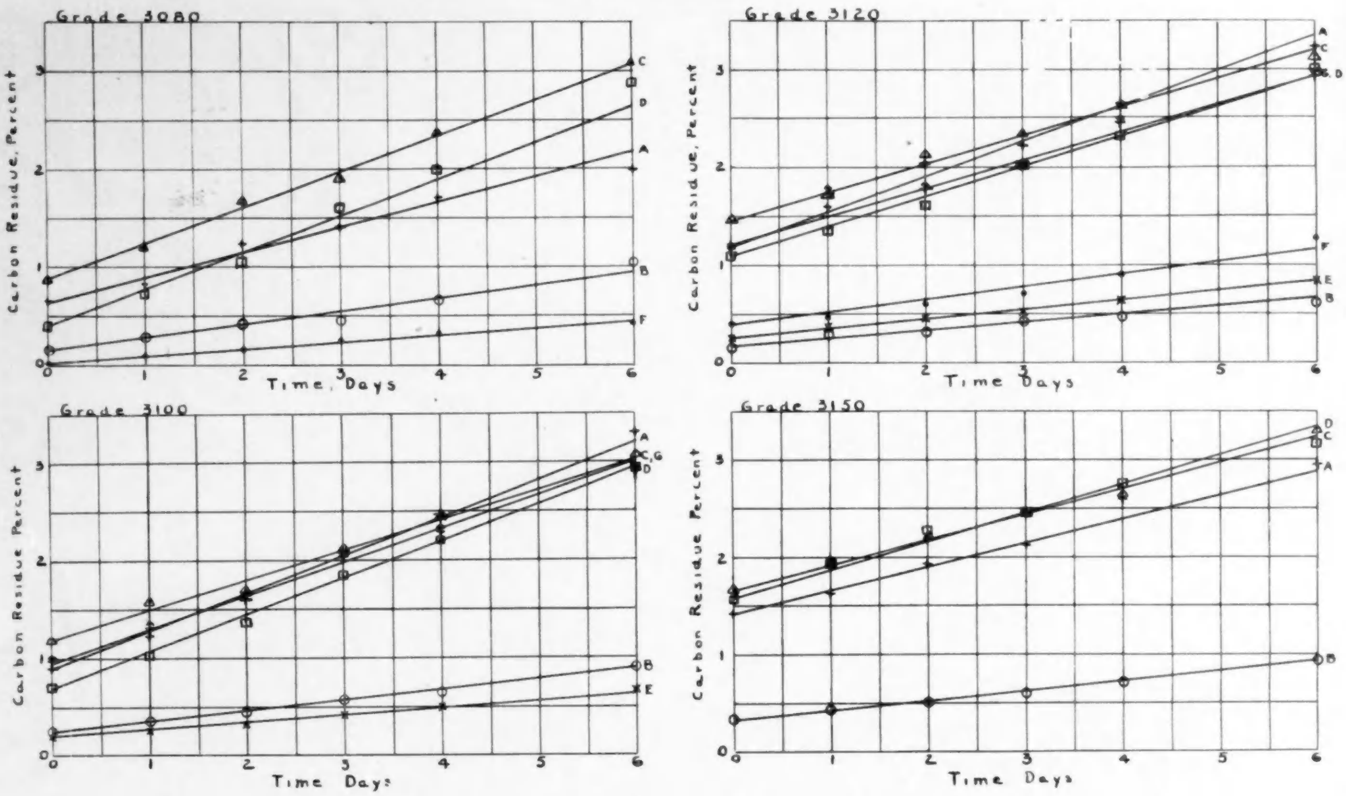

Fig. 5 – Change in Carbon Residue of Aviation Oils on Heating at 175 Deg. Cent. by Method A

Description of Laboratory Method B

The heating blocks employed for oil stability Method B were identical with those described in connection with Method A. The main difference between the two methods was the aerating of the oil samples in Method B, which was accomplished by means of aerating stirrers. These stirrers consisted essentially of 6½-in. lengths of ⅛-in. black iron pipe connected at the bottom to ⅛-in. black iron pipe tees closed at each end by plugs which were drilled out with a 4-mm. drill to form orifices for controlling the flow of air.

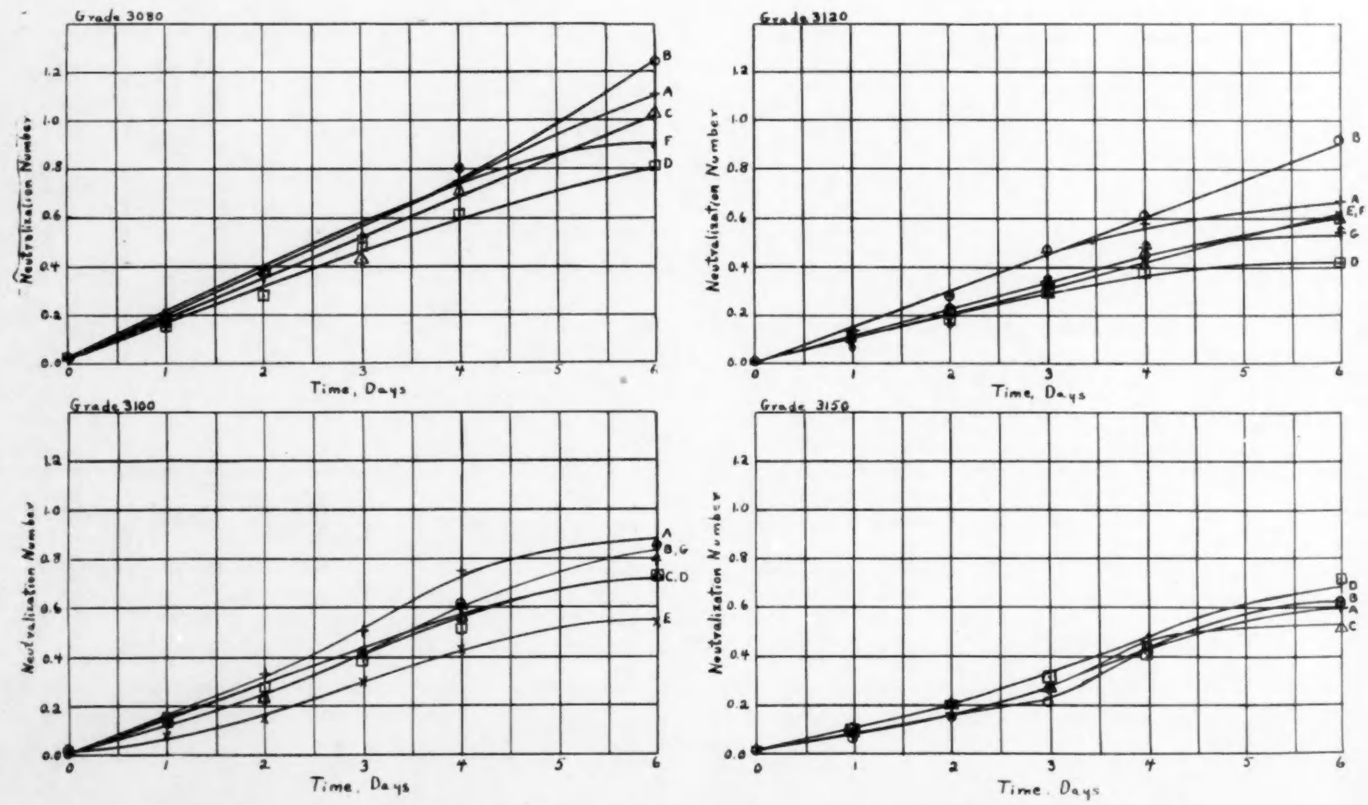

Fig. 6 – Change in Neutralization Number of Aviation Oils on Heating at 175 Deg. Cent. by Method A

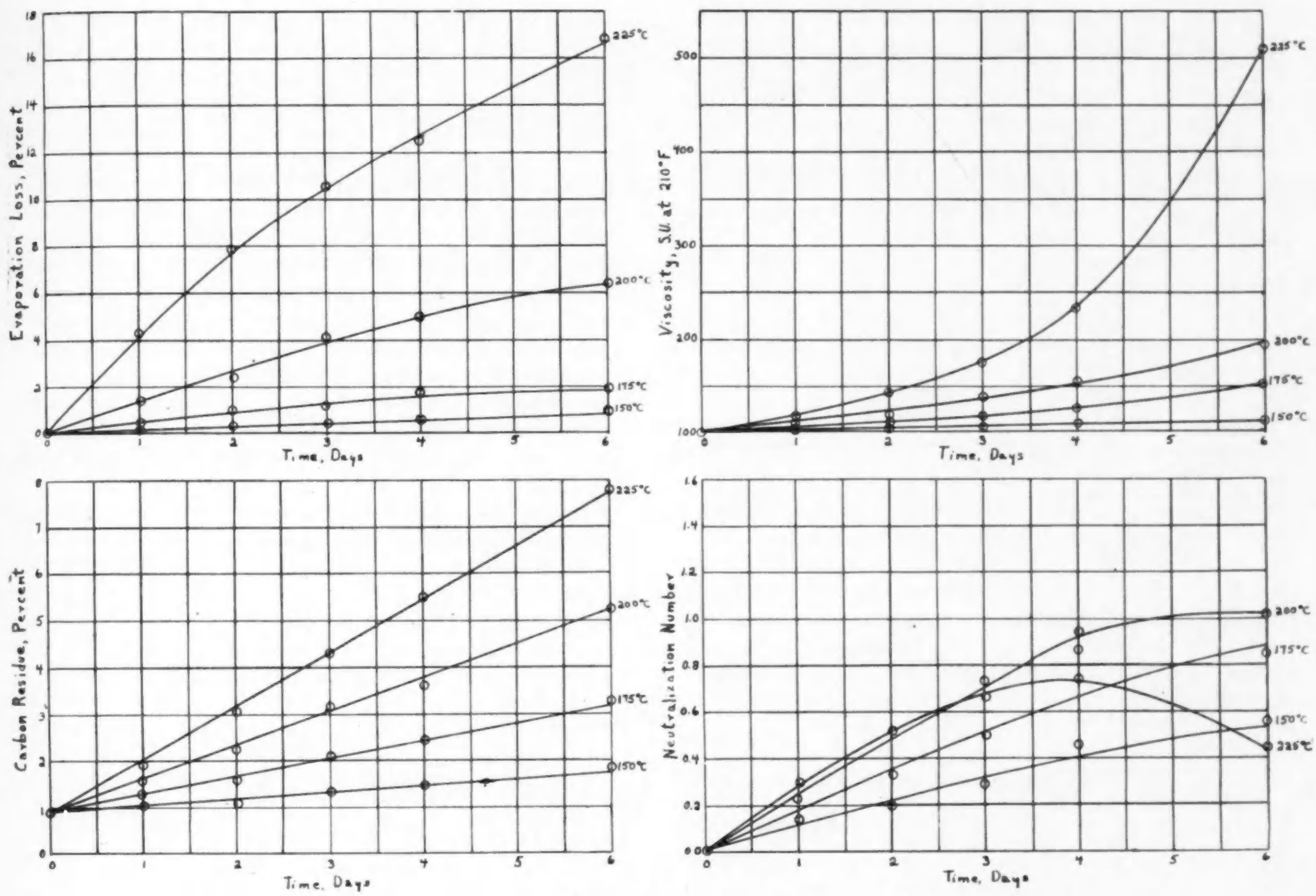

Fig. 7 – Change in Properties of Oil A100 on Heating at Various Temperatures by Method A

By means of special fittings, these stirrers were fastened with bayonet locks to six vertical shafts of a multiple-gear-reduction unit. The speed of rotation of the stirrers was about 750 r.p.m. which speed, in combination with the orifice size chosen, gave extremely fine subdivision of the air bubbles and kept the oil saturated with air at all times. Use of aerating stirrers has been found to be entirely satisfactory and much more convenient than the usual type of air jet and flowmeter. Two units equipped with aerating stirrers were available for this investigation and are shown at the left-hand side of Fig. 1. Since the multiple gear units were stationary, the heating baths were counterweighted and arranged so that they could be raised or lowered. The electrical control panel for the apparatus used in both Methods A and B is shown in Fig. 2.

The procedure of making a test was identical with that used in Method A. Since heating under aerating conditions is much more severe on the oil than without aeration, no tests were made at a temperature higher than 200 deg. cent. and shorter heating intervals were employed than with Method A. Data were obtained on 22 aviation oils heated for periods of ½, 1, 1½ and 2 days at each of the oil temperatures 150, 175 and 200 deg. cent. In the case of some of the more stable oils, longer periods of heating were used.

Description of Engine Tests

The engine employed for measuring the stability of the 22 aviation oils was a Pratt and Whitney Hornet, Model R1690-32. It was mounted on a torque stand and the power absorbed with a test propeller. Operation was at cruising speed (70 to 75 per cent of rated power) for 30-hr. runs with each oil. Each run was made in four periods, the first three being of 8-hr. duration and the last of 6-hr. duration. Preliminary to each operating period, the engine was idled for about 15 min. and, at the end of each period, idling for about 5 min. was allowed. Oil samples were withdrawn at the end of each period, and make-up oil was added after withdrawal of the test sample.

Fig. 8 – Effect of Temperature on Insoluble Material Formed by Oil A100 on Heating by Method A

Table 1A – Identification Data on Grade 3080 Aviation Oils

Test	Test Value A80	B80	C80	D80	F80
Viscosity, S.U.,					
at 210 Degrees Fahrenheit, sec.	79	72	79	79	79
at 130 Degrees Fahrenheit, sec.	336	271	344	404	363
at 100 Degrees Fahrenheit, sec.	776	603	812	1,090	874
Viscosity Index	99.5	106.1	95.0	60.6	87.4
Pour Point, Degrees Fahrenheit	10	0	5	—5	0
Carbon Residue, per cent	0.64	0.16	0.88	0.40	0.03
Flash Point, Degrees Fahrenheit	460	420	455	420	515
Fire Point, Degrees Fahrenheit	520	490	525	480	580
Neutralization Number	0.01	0.01	0.01	0.02	0.02
Sligh Oxidation Number	trace	1	1	1	1
Color, A.S.T.M.	7	2½	7	6	lighter than 1

Table 1B – Identification Data on Grade 3100 Aviation Oils

Test	Test Value A100	B100	C100	D100	E100	G100
Viscosity, S.U.,						
at 210 Degrees Fahrenheit, sec.	99	99	97	96	100	94
at 130 Degrees Fahrenheit, sec.	589	470	490	565	514	450
at 100 Degrees Fahrenheit, sec.	1,647	1,111	1,143	1,566	1,264	1,089
Viscosity Index	66.3	104.0	98.9	65.1	94.8	98.2
Pour Point, Degrees Fahrenheit	below 0	below 0	15	0	below 0	10
Carbon Residue, per cent	0.90	0.26	1.20	0.69	0.24	0.97
Flash Point, Degrees Fahrenheit	490	510	485	455	525	480
Fire Point, Degrees Fahrenheit	580	580	545	520	580	535
Neutralization Number	0.01	0.01	0.02	0.02	0.02	0.02
Sligh Oxidation Number	1	1	trace	1	1	1
Color, A.S.T.M.	5	2½	6	6	5	7

Since the engine was only being used as a means of producing changes in the oils and since it was very desirable that test conditions be as nearly identical as possible with the different oils, engine inspections between runs were not made. The engine was assembled originally so as to have a low oil consumption and was left unchanged until evidence of increasing oil consumption was obtained, at which time the engine was rebuilt to the original dimensions as closely as possible. The average oil consumption during the entire series of runs was less than 0.005 lb. per hp-hr. The capacity of the oil system was 100 lb. (12.5 gal.) which approximates the capacities of service installations. On the completion of the run with each oil, the oil system was cleaned out thoroughly so as to minimize contamination of the oil to be tested next.

Description of Test Oils

Twenty-two oils were tested in the engine and by laboratory Methods A and B under various conditions. Of the 22 oils, 5 were in the 3080 grade (Navy classification), 6 were in the 3100 grade, 7 were in the 3120 grade, and 4 were in the 3150 grade. Identification data on these oils are given in Tables 1A, 1B, 1C, and 1D. The prefix letter to the designation of the oil represents the company from whom the oil was obtained, whereas the number following the letter in the designation represents the Navy grade and is essentially equivalent to the Saybolt universal viscosity at 210 deg. fahr. Thus all oils with the same prefix letter were obtained from the same oil company.

Discussion of Laboratory Data

The volume of laboratory data obtained on the various oils is so large that it is not feasible to present all of it and, accordingly, an attempt will be made to abstract it and present typical sets of data and those which appear to be of greater interest. In Figs. 3, 4, 5, and 6 are shown the data obtained on all 22 oils when heated at 175 deg. cent. by Method A for various periods of time. Results obtained under this set of conditions showed the best correlation with the engine data and hence were chosen for illustration. Similar types of curves were obtained at other temperatures and also by Method B.

It is seen from Fig. 3 that there are marked differences in evaporation loss on heating the various oils, these being most noticeable with the two lighter grades. These differences are reflected in the viscosity curves shown in Fig. 4, although the curves are not consistently in the same order in both figures, indicating differences in the extent to which polymerization occurred. The carbon-residue curves in Fig. 5 are of

Table 1C – Identification Data on Grade 3120 Aviation Oils

Test	Test Value A120	B120	C120	D120	E120	F120	G120
Viscosity, S.U.,							
at 210 Degrees Fahrenheit, sec.	120	120	124	122	115	116	120
at 130 Degrees Fahrenheit, sec.	721	627	677	756	636	683	668
at 100 Degrees Fahrenheit, sec.	1,950	1,527	1,739	2,100	1,629	1,817	1,696
Viscosity Index	85.1	104.2	98.8	81.1	94.1	97.3	96.6
Pour Point, Degrees Fahrenheit	5	below 0	10	10	0	5	10
Carbon Residue, per cent	1.19	0.17	1.44	1.07	0.25	0.39	1.17
Flash Point, Degrees Fahrenheit	525	530	515	510	530	515	510
Fire Point, Degrees Fahrenheit	590	600	580	575	595	575	575
Neutralization Number	0.02	0.01	0.02	0.01	0.01	0.02	0.02
Sligh Oxidation Number	1	2	1	1	trace	2	1
Color, A.S.T.M.	7	2½	7	7	3½	4	8

Table 1D – Identification Data on Grade 3150 Aviation Oils

Test	Test Value A150	B150	C150	D150
Viscosity, S.U.,				
at 210 Degrees Fahrenheit, sec.	145	145	143	148
at 130 Degrees Fahrenheit, sec.	859	806	828	881
at 100 Degrees Fahrenheit, sec	2,233	2,013	2,191	2,314
Viscosity Index	99.2	105.7	98.9	99.0
Pour Point, Degrees Fahrenheit	10	0	10	20
Carbon Residue, per cent	1.41	0.33	1.67	1.56
Flash Point, Degrees Fahrenheit	550	560	535	525
Fire Point, Degrees Fahrenheit	620	635	595	605
Neutralization Number	0.03	0.01	0.02	0.02
Sligh Oxidation Number	trace	1	1	1
Color, A.S.T.M.	8	3½	7	7

interest and clearly differentiate between the conventionally refined and the solvent-refined oils. In a few cases the curves cross, likewise suggesting differences in the rate of polymerization. The neutralization number curves in Fig. 6 exhibit considerable similarity between all of the oils in any one grade, the major point of interest being the tendency in many cases to reach a limiting value for neutralization number.

Illustration of the effect of temperature on the stability of the oils, as obtained by Method A, is given in Figs. 7 and 8 for oil A100. As might be expected, evaporation loss, viscosity, and carbon residue increase consistently as the temperature of heating is raised. With neutralization number, however, there is a reversal of the curves. Thus, the acidity for any given period of heating increases with temperature up to 200 deg. cent. but, at 225 deg. cent., the curve passes through a maximum and the value after 6 days of heating at 225 deg. cent. is less than the neutralization number after 6 days of heating at 150 deg. cent. This phenomenon has been observed with a considerable number of the oils but, whether it is due to evaporation of the acids, inhibition of acid formation, or reversal of the chemical reaction, is not known. A somewhat similar effect can be observed in Fig. 8 where the curves for formation of naphtha insolubles cross. Thus, little insoluble material is formed at 150 deg. cent. and considerable insoluble material is formed at 175 deg. cent. The amounts formed at 200 and 225 deg. cent. are essentially equal and, at 4 days of heating, are about the same as the amount formed at 150 deg. cent. and much less than that formed at 175 deg. cent. After 6 days of heating, however, the amount of naphtha insoluble formed at 200 and 225 deg. cent., still essentially equal, is somewhat larger than the amount formed at 175 deg. cent. for the same time of heating. Similar effects have been observed with other oils, and they illustrate the sensitiveness of certain properties of the oil to temperature and length of time of heating at any given temperature. The relative positions of the temperature curves vary so widely with different oils that it is possible to rate a series of oils almost in any desired order merely by selection of test temperature and time of heating. It is this phenomenon which makes it so difficult to obtain a correlation with engine data. It also illustrates the practical impossibility of selecting *a priori* a set of laboratory test conditions for oil stability and of obtaining results of any significance.

The effect of aeration is illustrated in Fig. 9 where a comparison is made between the changes produced in oil A100 on heating at 175 deg. cent. for various periods of time by Methods A and B (without and with aeration respectively). It is seen that, under otherwise identical conditions, the changes produced in the oil are very much more marked when the oil is aerated. The most striking example is in connection with the naphtha insoluble where the amount formed is almost negligible after 2 days of heating without aeration but amounts to over 1.6 per cent when heated for 2 days with aeration. In general, only a few of the 22 oils formed any insoluble material even after heating for 6 days without aeration, whereas many of the oils formed appreciable amounts of insoluble material when aerated. All of the values for naphtha insoluble formed by Method B on heating at 175 deg. cent. are shown in Fig. 10. Absence of the curve in this plot for any oil indicates that the oil was so stable that it did not form any insoluble material even after heating for 5 days under these severe test conditions.

Engine and Laboratory Correlation

In the engine runs, oil is being consumed continually and make-up oil must be added from time to time. In the lab-

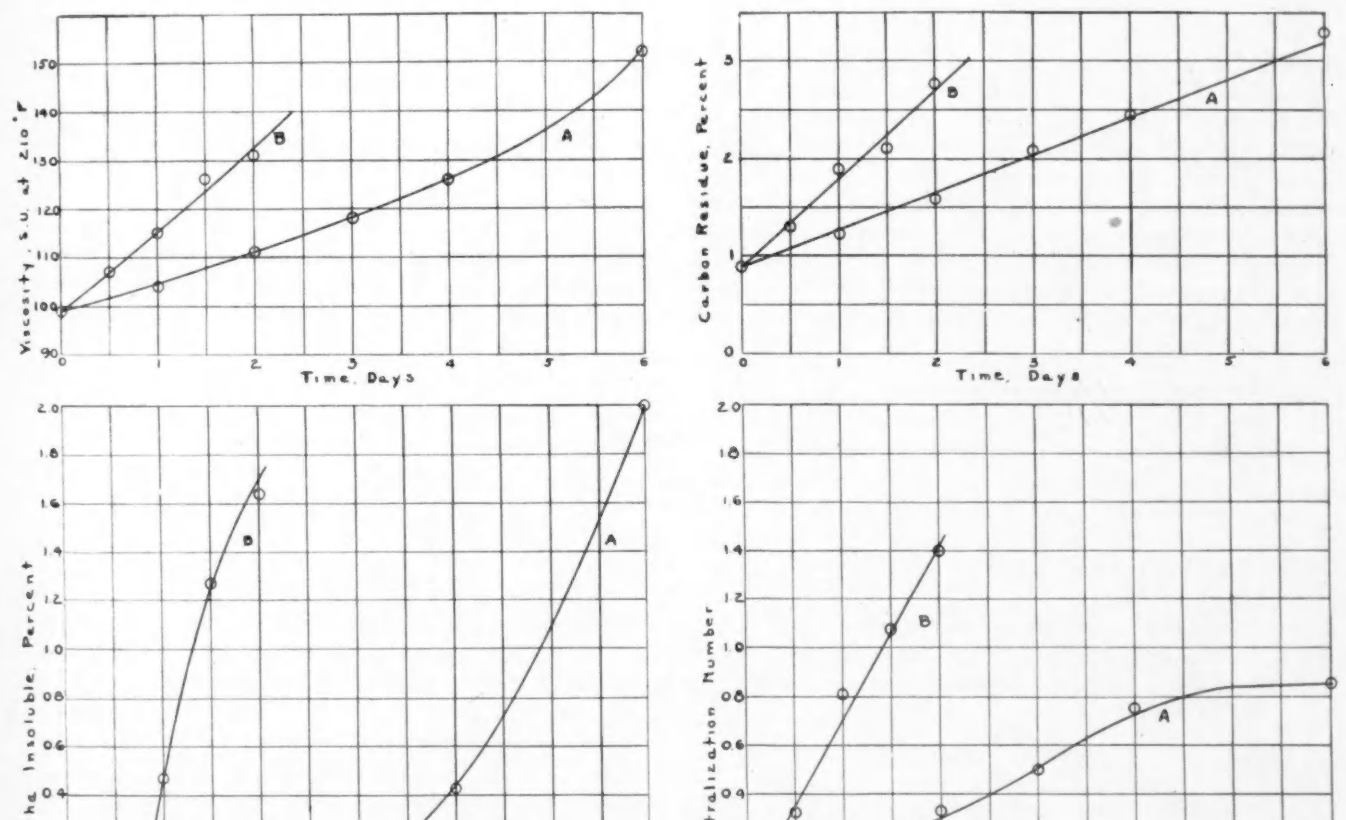

Fig. 9 – Comparison of Change in Properties of A100 on Heating at 175 Deg. Cent. by Methods A and B

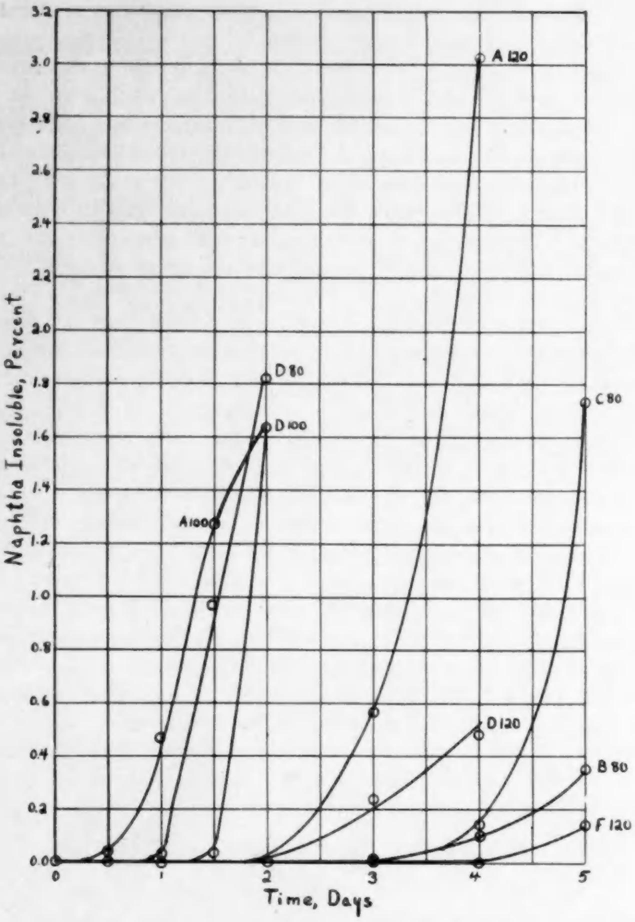

Fig. 10 – Values for Insoluble Material Formed at 175 Deg. Cent. by Method B

oratory tests, evaporation occurs at a slow rate but no make-up oil was added. Accordingly, in order to correlate the engine and laboratory values, it is necessary to transform both sets of data to a comparable basis. In the case of the engine data, it was assumed that the oil consumed at any instant was identical in properties with the oil in the supply tank at that instant. Accordingly, it was possible to compute the changes which would occur in the properties of the oil if none of it were consumed and if the same amount of oil was always present in the system. Hence using the oil consumption data and the analyses of the new and used oils, all of the engine data were corrected for oil consumption and for oil make-up. In the case of the laboratory data, it was assumed that none of the products of oxidation and polymerization were lost by evaporation, and hence all data were corrected back to the original weight of oil present. The engine and the laboratory data, transformed in the manner outlined to a comparable basis, are designated as corrected data.

The major interest in the present investigation was the condition of the various oils at the end of the 30-hr. engine run, and little reference will be made to values for the various properties of the oils obtained at intermediate times of engine operation. However, one example of the change in properties with time of engine operation is given in Fig. 11 for oil A100, the plotted points representing corrected engine data. It will be observed that the values for naphtha and chloroform insolubles become comparatively high but the difference between them, representing asphaltenes formed,

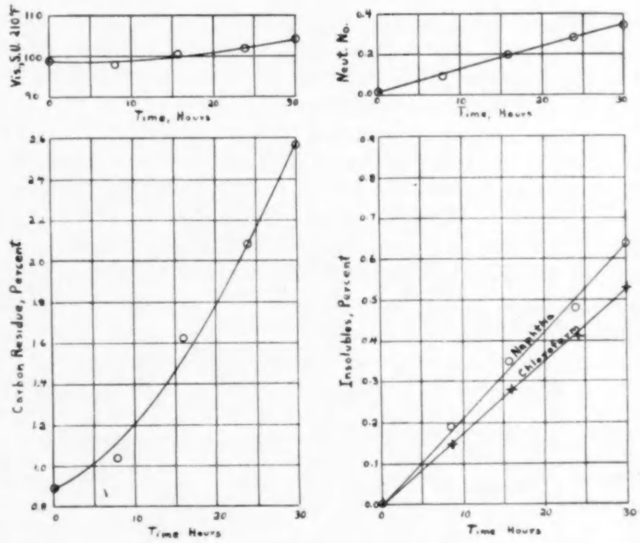

Fig. 11 – Change in Properties of Oil A100 During 30-Hr. Engine Run

is small. A100 is the least stable oil run in the engine tests from the standpoint of sludge formation and, with most oils, the difference between the naphtha and chloroform insoluble was negligible. Thus, in obtaining a correlation between

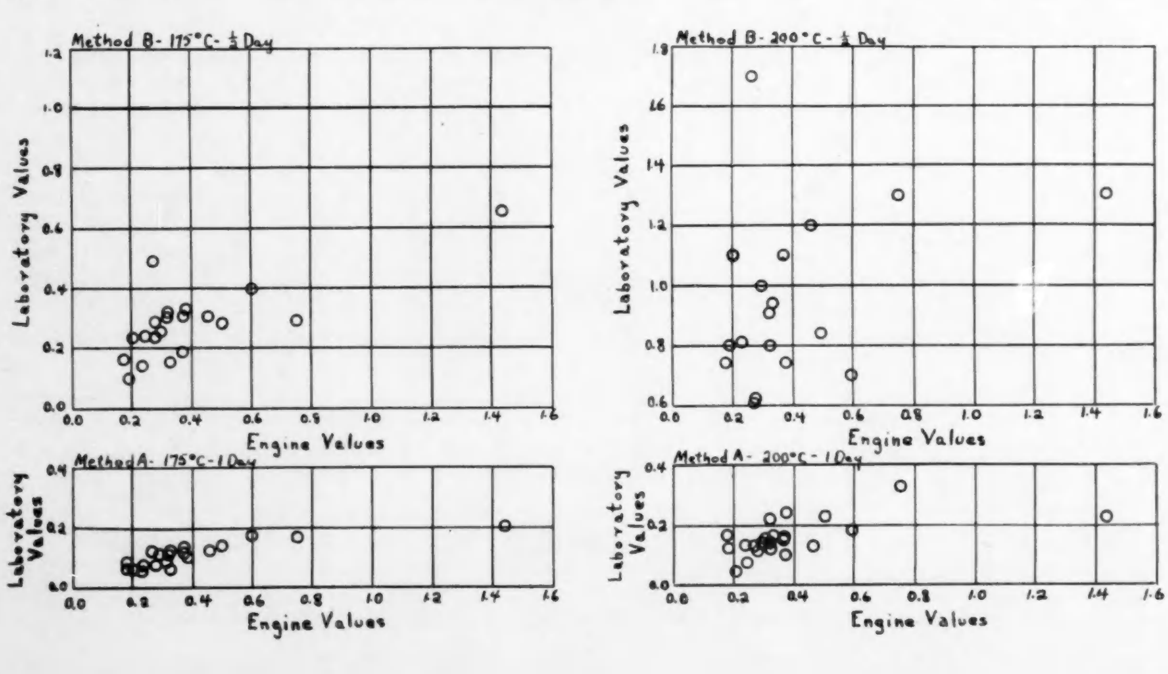

Fig. 12 – Comparison of 30-Hr. Engine Data on Neutralization Number for 22 Aviation Oils and Laboratory Data Obtained Under Various Test Conditions

the engine and laboratory data, it was necessary to rely on other properties of the oil than formation of asphaltenes.

Since laboratory data were obtained on all 22 aviation oils under 32 different sets of conditions covering both of the basic methods A and B, it is not feasible to illustrate the comparison between the engine data and the laboratory values by all 32 methods. However, in Figs. 12 and 13, a comparison is given between the corrected engine data on neutralization number and carbon residue, corresponding to 30 hr. of operation, and the corrected laboratory data by the four laboratory methods which showed the best correlation. These plots show the increases in neutralization number and carbon residue obtained in the engine and laboratory tests, and represent the corrected data minus the values for the unused oils. It is apparent that there is a marked lack of correlation with the laboratory data by Method B and that the best correlation with the data by Method A is obtained at a temperature of 175 deg. cent. A further illustration of the correlation between the engine data and the laboratory data obtained by heating for 1 day at 175 deg. cent. by Method A is given in Figs. 14 and 15. Using the engine data as a basis for computing laboratory values, the average difference between observed and computed values was 0.01 for neutralization number and 0.04 for carbon residue, deviations which are within the experimental error of the measurements.

It appears, therefore, that heating of oils in the laboratory with an exposed surface but without aeration for a period of 24 hr. at a temperature of 175 deg. cent. will produce changes in their properties which are quantitatively related to the changes which take place up to at least 30 hr. in a Pratt and Whitney Hornet engine (R1690-32). Although the preceding correlation is necessarily based on a somewhat theoretical consideration of engine operation without any oil consumption, the laboratory data will serve to rate oils in the proper order regardless of the oil consumption, assuming that the differences in oil consumption are not too large between any two oils under comparison. In this case, less change will be produced in the oil as the oil consumption increases, but the changes can be computed for any known rate of oil consumption. Although the engine data have all been obtained on one model of engine, it is believed that the laboratory test method is reasonably significant for application to all air-cooled aviation engines of moderate output (horsepower per cubic inch displacement). The significance of the laboratory method when applied to engines of high output can only be decided when further tests are made on engines of this type. A partial check on the significance of the method is being obtained from analyses of oils drained from a variety of engines in service.

One of the major reasons why methods developed for determination of the stability of automobile engine oils have not been satisfactory for application to aviation oils is that these methods have used aeration, whereas the concentration of oxygen in the crankcase of an aviation engine appears to be relatively low. Also, most of the methods proposed for automobile oils have been concerned with the formation of insoluble material whereas, with good aviation oils, extremely little insoluble material outside of "blowby" carbon is formed in service, except possibly in cases where the oil consumption is very low and the oil is used for excessive periods of time without changing. Heating at 175 deg. cent. without aeration eventually will produce insoluble material and, although it may take longer to rate oils according to their sludging tendency by this method, it is believed that the results will have much more significance than if attempts are made to expedite formation of insoluble material by use of aeration or higher test temperatures. This statement is not necessarily applicable to tests for estimating the ring-sticking tendencies of oils, for a high test temperature probably is required for this special application in order to simulate conditions in the ring grooves.

Although the laboratory method (heating at 175 deg. cent. without aeration) chosen as being most significant is considered to be satisfactory, at least for present-day aviation engines of moderate output, there is one theoretical objection to it. In the engine, the oil is oxidized and polymerized at a variety of temperatures since there is a considerable tempera-

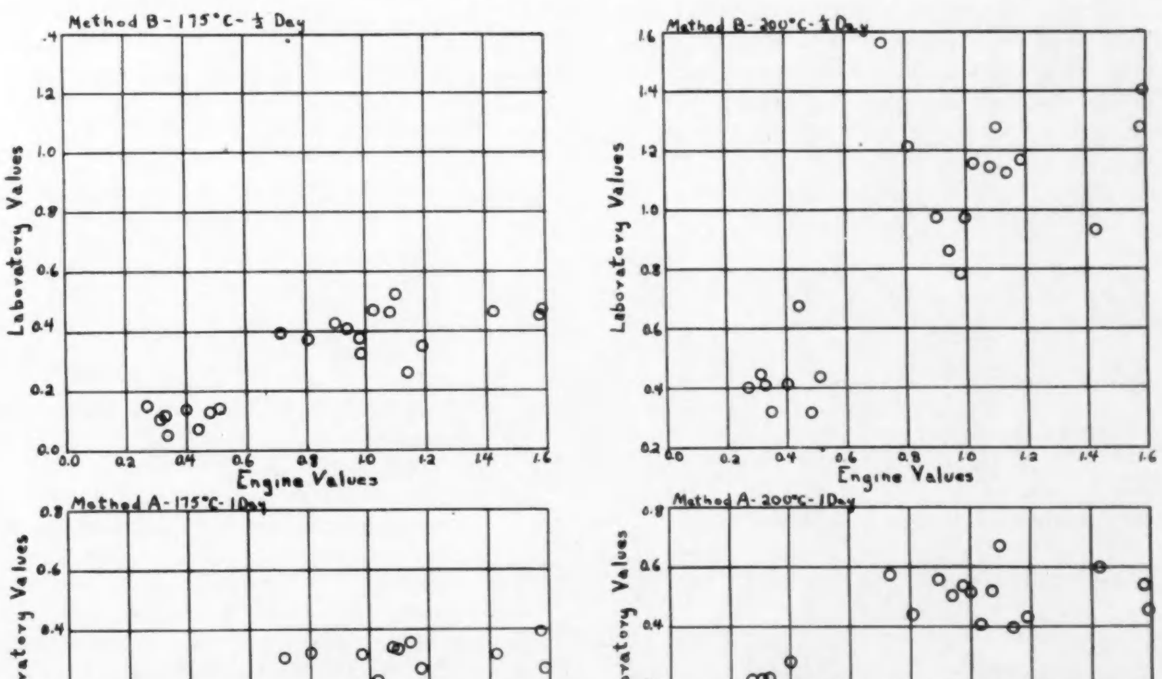

Fig. 13 – Comparison of 30-Hr. Engine Data on Carbon Residue for 22 Aviation Oils and Laboratory Data Obtained under Various Test Conditions

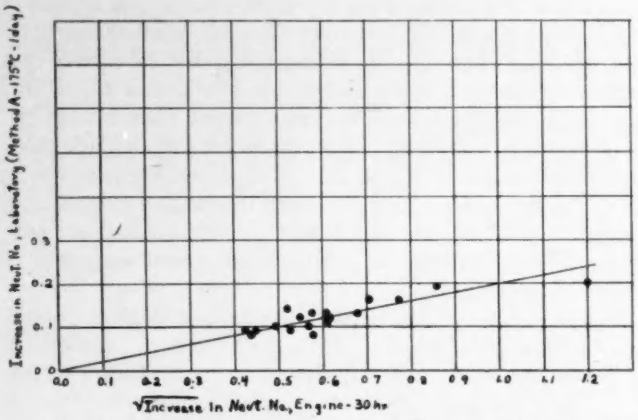

Fig. 14 – Correlation Between Neutralization Numbers by Engine and Laboratory Methods

ture gradient down the cylinder walls. In the laboratory method, on the other hand, the oil is changed at a constant temperature. A preferable laboratory method appears to be one in which the oil is circulated and exposed to a wide range of temperatures in each cycle. A method of this type (Method C) is now under investigation at the National Bureau of Standards, as mentioned at the beginning of this paper, and results by this method will be reported at a later date.

Conclusions

In summarizing the work done so far in the investigation of the stability of aviation oils, the following conclusions appear justified:

(1) Laboratory methods for oil stability can be developed which will rate a series of oils in almost any order, depending upon the test conditions.

(2) Methods involving aeration are much too severe for stability tests of aviation oils and do not show correlation with engine data.

(3) The most significant set of test conditions found involves heating of aviation oils without aeration at a temperature of approximately 175 deg. cent. Laboratory data obtained under these conditions correlate satisfactorily with the service performance of the oils in aviation engines of moderate output.

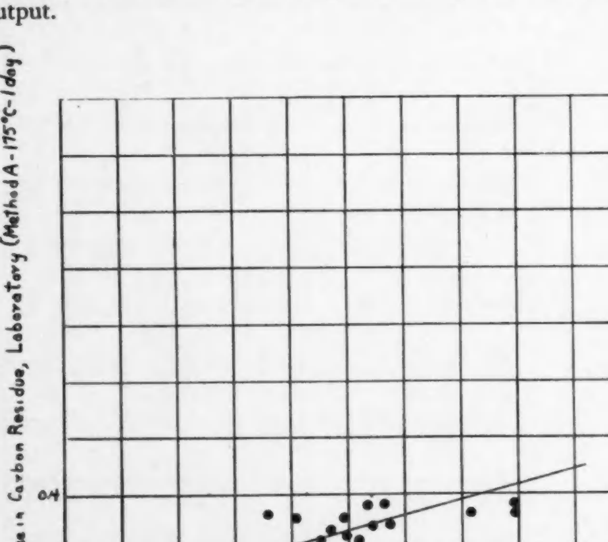

Fig. 15 – Correlation Between Carbon Residues by Engine and Laboratory Methods

Acknowledgment

This investigation was conducted in cooperation with the Bureau of Aeronautics, Navy Department, who furnished the aviation engine and parts and assumed responsibility for a large share of the cost of the project. During the past two years, the oil-stability investigation has been a part of the program of the N. A. C. A. Subcommittee on Aircraft Fuels and Lubricants.

The aviation engine runs were made by the Automotive Power Plants Section of the National Bureau of Standards, with G. Ellis in immediate charge and with E. R. Paul and B. M. Aldrich as the senior engine operators. Acknowledgment is made to R. V. Higgins, D. A. Morgan, and C. M. Murphy, Jr., who assisted in the development of improved laboratory methods for used oil analysis and who conducted a large share of the laboratory test work on the oils.

Tractor Air-Cleaner Performance in Dust Clouds

THE paving of our major highways has diminished the importance of air cleaners for automobile engines, but the dirt-moving in highway construction creates a dust environment that often overtaxes even the heavy-duty air-cleaner equipment usually found on road construction equipment engines. The quantity ratio of usual paved highway dust to highway construction dust is something like 1:4000. Even under extremely dusty conditions in the Southwest the 100 gm. of dust per day mentioned by R. F. Norris in a recent paper caught by an automobile is only about one-twentieth of the catch of ½ pt. per hr. often found with tractors working with graders. Of course, the dust catch varies greatly with changing conditions, but the preceding quantitative observations help one to visualize the magnitude of the problem of tractor air-cleaner performance in clouds of dust raised by equipment moving dirt.

The surface soil particles lifted and carried in dense clouds by strong winds in dust and sand storms are generally much larger in size than machine-raised dust floating higher than 4 ft. above ground in still air. Therefore, the only special design problems for air-cleaners to be used in dust storms concern rapid removal and large holding capacity. E. J. Graham in a recent article reports catches of 2 qt. of sand in 110 miles in Colorado which is about five times the high rate found in road working.

There is little question of the effectiveness of the regular oil-bath air cleaners if they always are serviced properly. But, under severe dust conditions, the frequent shutdowns of 5 to 20 min. for proper servicing often interferes with the tractor work schedule and is always an objectionable duty which everyone wishes to avoid. Consequently, there are many recurring cases of air-cleaner failure and poor engine operation which have created a demand for new types of air cleaners.

To judge the merit of these new cleaners it is first necessary to study the characteristics of the usual oil-bath cleaner in relation to failure from overloading. It is not strictly proper to group the different makes of oil-bath air cleaners and talk only in general terms, but one would be lost trying to consider the effect of detail differences in the short space available for this discussion. We have found by experiment that all the oil-bath air cleaners now in large use show practically the same effectiveness under a few general conditions.

Excerpt from the paper of the same title by F. A. Brooks, presented at the Northern California Section Meeting of the Society, April 13, 1937.